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# 1. INTRODUCTION

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As part of its Industries of the Future strategy, the Industrial Technologies Program within the U.S. Department of Energy’s (DOE) Office of Energy Efficiency and Renewable Energy works with energy-intensive industries to improve efficiency, reduce waste, and increase productivity. These seven Industries of the Future (IOFs) – aluminum, chemicals, forest products, glass, metal casting, mining, and steel – rely on several other so-called “supporting industries” to supply materials and processes necessary to the products that the IOFs create. The supporting industries, in many cases, also provide great opportunities for realizing energy efficiency gains in IOF processes.

The Industrial Technologies Program, therefore, works with these industries in much the same way it does with the IOFs: funding cost-shared research and development (R&D) that addresses industry-defined priorities as well as national goals for energy and the environment. In many cases, projects focus on potentially high-payoff technologies that are too risky or costly to attract the magnitude of private funding necessary to achieve breakthroughs.

The purpose of this energy and environmental profile is to provide qualitative and quantitative information regarding the six supporting industries that are working in partnership with the Industrial Technologies Program for improved energy efficiency. These six industries are:

- Advanced Ceramics
- Carbon Products
- Forging
- Heat Treating
- Powder Metallurgy
- Welding

Table 1-1 summarizes key economic and energy consumption data for these industries

## **ADVANCED CERAMICS**

Advanced ceramics is an emerging technology area that represents a variety of materials and applications characterized by their stability, corrosion-resistance, and toughness. These materials have the potential to deliver energy, environmental, and economic benefits to the IOFs in the form of higher efficiencies, increased production, and lower operations and maintenance costs.

**TABLE 1-1. ECONOMIC AND ENERGY CONSUMPTION DATA FOR SUPPORTING INDUSTRIES<sup>a</sup>**

<b>Supporting Industry</b>	<b>Value of Shipments (\$ billion)</b>	<b>Number of Employees</b>	<b>Estimated Energy Consumption (10<sup>12</sup> Btu)</b>
Advanced Ceramics	\$8.5	ND	ND
Carbon Products	\$2.8	11,000	107
Forging	\$6.0	36,000	28-37
Heat Treating	\$20	ND	458
Powder Metallurgy	\$7.3	40,000	16
Welding	\$4.0	18,300 <sup>b</sup>	129

ND No data available

<sup>a</sup> See Chapters 2-7 for details regarding data sources and assumptions for each industry.

<sup>b</sup> Number of employees working in welding equipment suppliers; number of welders working in all industries is estimated at 500,000 (American Welding Society).

The United States currently accounts for \$8.5 billion, or 35 percent, of the global advanced ceramics market. Forecasts project a global market growth of eight percent per year between 2000 and 2005, totaling \$11.7 billion in 2005. Within the U.S. market, electronics account for 64.7 percent of advanced ceramics applications, followed by chemical and environmental applications (18.7 percent), ceramic coatings (10.2 percent), and structural ceramics (6.4 percent).

### **CARBON PRODUCTS**

The carbon products industry is a diverse, cross-cutting industry employing approximately 11,000 workers and supplying critical materials and components to some of the United State's most essential industries, including aluminum, steel, chemicals, aerospace, electronics, recreation, and environmental protection. A large portion of the industry is built on the recovery and processing of byproducts from other primary operations. The estimated value of shipments of carbon products in 2001 totaled approximately \$2.8 billion. Purchased energy for 2001 totaled approximately 2 billion kWh.

### **FORGING**

Forging is the process of pressing, pounding, or squeezing malleable metals under great pressure to form high-strength parts known as forgings. By refining the grain size and flow of the metal, forging improves its structure and increases its resistance to fatigue and impact. Commonly forged metals include carbon alloys and stainless steels, very hard tool steel, aluminum, titanium, brass, copper, and high-temperature alloys. The total forging industry output in North America is estimated to exceed \$6 billion annually, achieved by some 25,000 workers predominantly in facilities that process iron and steel. The forging industry consumes approximately 1.67 billion kWh of

electricity each year, a relatively low amount compared to other technologies that produce finished or semi-finished parts. Based on an average specific heat of 1 to 3 Btu/lb/K for every pound of steel or aluminum forged, estimates place total annual energy consumption for the industry between 28 and 37 trillion Btu.

## **HEAT TREATING**

The energy-intensive heat treating industry plays a vital role in many metal manufacturing processes. Heat treating is the process of heating and cooling a material in such a way as to develop a specific structure, chemical composition, and physical properties. The heat treating industry is directly related to the metal-producing and secondary processing industries, accounting for \$20 billion in the United States annually and \$75 billion worldwide. In the United States, approximately 5,000 facilities operate roughly 55,000 furnaces, 66 percent of which are gas-fired and the remainder of which are electrically heated. The furnaces and associated equipment account for approximately 458 trillion Btu of annual energy use, with gas-fired furnaces consuming 337 trillion Btu (329 billion cubic feet natural gas) and electrically heated furnaces the balance of 121 trillion Btu.

## **POWDER METALLURGY**

Powder metallurgy (P/M) is a useful approach for producing a wide range of both commercial and developmental materials and products. The automotive sector consumes 70 percent of all P/M components, the majority of which are created from iron and steel powders. P/M is also useful for producing small lots of new materials, as existing commercial powders can often be blended together to produce the desired composition, avoiding the costs and facilities required for custom melting. P/M can produce a wide range of product forms, ranging from billets to pre-forms to near-net-shape parts.

The P/M industry in the United States is commonly divided into powder producers (value of U.S. shipments near \$2 billion in 2000; worldwide production exceeding 1 million tons annually), tooling and equipment makers (approximately 100 U.S. companies accounting for \$300 million in sales annually), and component and product producers (estimated 250 U.S. producers accounting for \$5 billion in sales annually).

## **WELDING**

Welding is a joining process that uses heat, pressure, or both to fuse the surface of two distinct elements and form a single unit. Over 100 processes comprise the family of welding technologies, which are used in a vast array of manufacturing and construction industries. Welding can be applied to metals, polymers, and ceramics, as well as emerging composite and engi-

needed materials. Welding expenditures represent a substantial contribution to the U.S. economy, as many industries that employ welding processes provide the backbone for our nation's defense and infrastructure. Revenue from these industries totaled over \$3.1 trillion in 2000, representing approximately one-third of the total U.S. Gross Domestic Product. Energy consumption for the industry is estimated to be 129 trillion Btu annually.

### **ENVIRONMENTAL ISSUES**

Environmental regulations affect the supporting industries throughout all stages of manufacturing and forming processes. The following major environmental regulations apply to all manufacturing industries.

#### **EMISSIONS AND THE CLEAN AIR ACT**

The Clean Air Act and its amendments, including the Clean Air Act Amendments of 1990 (CAA-A), have established the National Ambient Air Quality Standards (NAAQS) to limit levels of six pollutants considered harmful to public health and the environment. These six "criteria" pollutants are carbon monoxide, nitrogen dioxide, sulfur dioxide, ozone, particulate matter, and lead. Under the Act, each state must develop an implementation plan to identify sources of air pollution and determine what reductions are required to meet Federal air quality standards.

Recent revisions to the NAAQS for particulate matter have significantly impacted many industries. Until 1997, the official indicator for particulate matter was PM<sub>10</sub>—particles less than or equal to 10 microns in diameter. In 1997, a new, separate standard was created for particles less than or equal to 2.5 microns in diameter (PM<sub>2.5</sub>). New national health standards for ozone and PM<sub>2.5</sub> were adopted by EPA in July 1997, but a 1999 Federal court ruling blocked implementation of most of these standards. In early 2001, the U.S. Supreme Court reversed the decision of the lower court and upheld the legality of the new standards.

New facilities, as well as expansions of existing facilities or process modifications, must comply with the 1990 CAAA New Source Review (NSR) requirements. For areas that do not meet CAAA requirements but meet NAAQS for a given pollutant, permits require the new source to meet the lowest achievable emission rate (LAER) standards. Also, the new source must procure reductions in emissions of all pollutants equal to or lower than other facilities in the area. For areas meeting the NAAQS, permits require the best available control technology (BACT), with continuous air quality testing required for one year.

#### **HAZARDOUS AIR POLLUTANTS**

Section 112 of the Clean Air Act requires EPA to list categories of major sources of hazardous air pollutants (HAPs) and establish national emissions

standards for those source categories. Sources that emit any of 188 HAPs were originally listed in Section 112 of the CAA; revisions are found in 40 CFR Part 63, Subpart C. The Act requires that EPA promulgate standards by November 15, 2000 for both new and existing sources based on industry-specific maximum achievable control technology (MACT). The MACT is defined as the control technology achieving the maximum degree of HAP reductions, taking into account cost and other factors.

EPA anticipated difficulty in adopting enforceable NESHAPs for the many sources of HAPs. Therefore, the 1990 CAA amendments state that if EPA misses a promulgation deadline for an applicable source category by 18 months (the May 15, 2002 “MACT hammer” deadline, as it is known), states must develop standards for that source. In addition, the owner/operator of a major source of a HAP (defined as having the potential to emit greater than 10 tons per year of any one HAP, or the potential to emit 25 tons per year of any combination of HAPs) must implement emissions standards equivalent to the MACT standards EPA would have established. When EPA eventually issues a national MACT standard, that standard replaces those established by any states.

In November 2002, EPA gave notice that additional area (non-major) source categories, including carbon black production and iron and steel forging, will face HAP control standards under the urban air toxics strategy. This strategy dictates that EPA must ensure that 90 percent of 30 HAPs (the urban air toxics) from area sources are subject to either MACT or some form of Generally Available Control Technology (GACT) standards. For area sources of HAPs, EPA is allowed to promulgate GACT standards in lieu of MACT standards.

### **EFFLUENTS AND THE CLEAN WATER ACT**

Water is an integral part of industrial processes:

- To cool equipment, furnaces, and products
- To remove scale from products
- As a source of steam
- As a medium for lubricating oils and cleaning solutions
- For air pollution control in wet scrubbers

The Clean Water Act (CWA) regulates both direct and indirect discharges of toxic pollutants, total suspended solids, oil, grease, and other pollutants. Effluent limitation guidelines and standards for industry have been established by EPA in 40 CFR 420. These standards are implemented through the permit program of the National Pollutant Discharge Elimination System (NPDES) of the Clean Water Act, and through state and local pretreatment programs. The regulated pollutants include the following:



- Conventional Pollutants - Total suspended solids, oil, grease, and pH
- Nonconventional Pollutants - Ammonia-nitrogen and phenols
- Priority or Toxic Pollutants - Total cyanide, total chromium, hexavalent chromium, total lead, total nickel, total zinc, benzene, benzo(a)pyrene, naphthalene, and tetrachloroethylene

A facility that intends to discharge into the nation's waters must first obtain a permit. Some metals industries often recycle their wastewater both "in-plant" and "end-of-pipe" to reduce the volume of discharge. Process wastewater is usually filtered and/or clarified on-site before being directly or indirectly discharged. Oil and greases are removed from the process wastewater by oil skimming, filtration, and air flotation; these oils can then be reused. The remaining sludge contains waste metals and organic chemicals. Iron in the sludges can be recovered and reclaimed.

In January 2001, EPA proposed new discharge limits for the metal products industries (including metal forming and metal powders). In June 2002, the agency announced that it was considering significant changes to the proposed limits, in part because the cost of complying with the new standards had been underestimated.

#### **SOLID AND HAZARDOUS WASTE**

The Resource Conservation and Recovery Act (RCRA) of 1976, which amended the Solid Waste Disposal Act, established regulations on the handling and disposal of solid and hazardous waste. The Hazardous and Solid Waste Amendments of 1984 strengthened RCRA's waste management provisions. Regulations promulgated pursuant to Subtitle C of RCRA establish a system governing hazardous waste from the point of generation to disposal.

Applicable wastes from the industries in this profile include sludge (which may contain heavy metals); inorganic acids and organic solvents, if they are spilled or disposed of prior to use; spent solvents; and wastes from the "D" series, which designates materials that exhibit a hazardous waste characteristic. The RCRA requirements for the industry also apply to any company that transports, treats, stores, or disposes of waste.

#### **TOXIC RELEASES**

The Emergency Planning and Community Right-to-Know Act (EPCRA) improves community access to information regarding chemical hazards, and facilitates the development of chemical emergency response plans by state and local governments. EPCRA requires manufacturing facilities with ten or more employees that manufacture, process, or use specified chemicals in amounts greater than threshold quantities to submit an annual toxic chemical

release report. This report covers releases and transfers of toxic chemicals to various facilities and environmental media, and allows the EPA to compile the National Toxics Release Inventory (TRI) database.

### **OTHER ENVIRONMENTAL CHALLENGES**

Some of the biggest challenges facing the supporting industries (in particular forging, heat treating, powder metals, and welding) are driven by customers rather than regulators. For example, many automakers will require their first tier suppliers to comply with ISO 14000 standards for Environmental Management Systems. Although most of the supporting industries have adopted environmental management practices for operating their production facilities and monitoring their compliance status, they have not embraced a standard set of environmental practices. In addition, the systems set up to demonstrate compliance with federal, state, and local regulations will not necessarily satisfy the requirements of ISO 14000 (Duckett 2002).

Other emerging management challenges for the industries include:

- Accounting for NO<sub>x</sub> allowances and Emission Reduction Credits (ERCs), both of which can be bought and sold to other facilities
- Tracking emissions for those facilities accepting Plantwide Emissions Limits (PALs)

The following chapters provide detailed information regarding the economic, technical, energy, and environmental status of each of the supporting industries. These six industries will continue to play a vital role in DOE's ongoing efforts to improve energy efficiency, reduce wastes, and increase productivity in the industrial sector.



## 2. ADVANCED CERAMICS

### 2.1 INDUSTRY OVERVIEW

Advanced ceramics are also commonly referred to as industrial ceramics, engineered ceramics, enhanced ceramics, or fine ceramics. Aside from the nomenclature, advanced ceramics represent a variety of materials that are characterized for their stability, corrosion-resistance, and toughness. Their use in a wide range of applications can lead to energy, environmental, and economic benefits; lower maintenance; higher efficiencies; and lower operating costs. Advanced ceramics have many of the desirable characteristics of conventional ceramic materials, without many of the conventional flaws. Though the properties of advanced ceramic products vary by design, they tend to have high-temperature strength, high resistance to friction wear, high chemical resistance, low thermal expansion, and low thermal conductivity.

Currently, the advanced ceramics industry is not represented by a specific code in either the Standard Industry Classification System (SIC) or the North American Industry Classification System (NAICS). Instead, advanced ceramics represents fractions of other classified industries as shown in Table 2-1.

### 2.2 INDUSTRY PERFORMANCE AND MARKET TRENDS

TABLE 2-1. INDUSTRIES USING ADVANCED CERAMICS

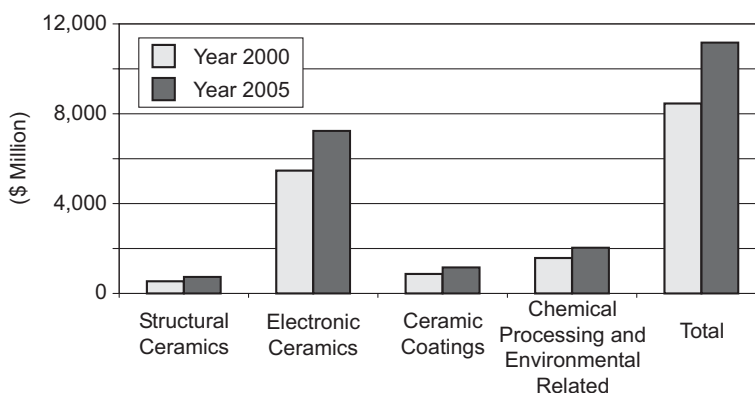
Application Type	Description	SIC Code	NAICS Code
Structural Applications	Motor Vehicle Parts and Accessories; Steam, Gas, and Hydraulic Turbines; Motors and Generators; Aircraft Engines and Parts	3714 3511 3621 3724	Various 33611 335311 336412
Mechanical Applications	Cutting Tools, Ball and Roller Bearings, Pumps and Pumping Equipment, Fabricated Metal Products	3545 3562 3561 3499	332212, 333515 332991 333911 Various
Electronic Applications	Electronic Capacitors, Semiconductors, Electronic Resistors, Other Electronic Components	3675 3674 3676 3679	334411 334413 334415 Various

Between 1990 and 2000, the advanced ceramics industry grew at a steady eight percent per year. However, recent cutbacks in federal R&D funding and consolidation in the industry have prevented sharper growth. Advances in

near net-shape processing techniques have stagnated while manufacturing costs have remained high, as machining costs can represent as much as 75 percent of total manufacturing costs.

The overall U.S. advanced ceramics market in 2000 was estimated at \$8.46 billion. Electronic applications represented 64.7 percent of the market, followed by chemicals and environmental applications (18.7 percent), ceramic coatings (10.2 percent), and structural ceramics (6.4 percent). The Business Communications Company (BCC) forecasted a market growth rate of 8 percent per year between 2000 and 2005, totaling \$11.17 billion in 2005. The forecast indicates that in 2005 the various advanced ceramics market segments will maintain similar market shares to those on 2000, with electronic applications representing 64.8 percent of the market (see Figure 2-1). The Freedonia Group predicts an even more optimistic forecast of 9 percent per annum growth between 2003 and 2007.

**FIGURE 2-1. U.S. MARKETS FOR ADVANCED CERAMICS COMPONENTS, 2000-2005**  
(\$ MILLION)



SOURCE: CERAMIC INDUSTRY MAGAZINE ONLINE, 2003.

In 2001, after achieving record sales the previous year, revenues for many advanced ceramic companies declined by as much as 20 to 60 percent, as the electronic, telecommunications, and high-tech industries stagnated. The industry was also affected by a severe downturn in the semiconductor capital equipment sector. As a result, many companies decided to reduce costs by closing facilities and decreasing employment. To improve their profit margins, companies also developed new products and expanded their market share for existing products. In the beginning of 2002, these profit-making strategies began to show a positive effect, with earnings above those of the last quarter of 2001.

## U.S. GLOBAL POSITION

In 2000, advanced ceramics represented a \$24 billion worldwide industry, 35 percent of which was accounted for by the United States (\$8.5 billion). Between 1990 and 1994, the United States witnessed 32 percent of the world's advanced ceramics patent families; however, the largest number of patents was recorded by Japan, with 39 percent of the total.

## INDUSTRY STRUCTURE

Advanced ceramics include oxides, non-oxides, and various particulate, whisker, and continuous fiber-reinforced ceramic composites. High-purity ceramic coatings are another category of advanced ceramic materials. Commercial advanced ceramics include wear parts, cutting tools, bearings, bio-chemicals (artificial joints, dentures, etc.), electro-chemical devices, heat transfer parts, ceramic filters, fiber optics, and sporting goods. Other advanced ceramic applications include broad categories, such as space shuttle cones and tiles, as well as gun liners, ceramic armor, and ammunition parts.

Advanced ceramics can be classified under the following three categories:

**Monolithic Ceramics** — Monolithic ceramics are oxide and non-oxide chemicals made up of a single material. Advanced monolithic ceramics include oxides (aluminum oxides, alumina-zirconia-silica, and transformation-toughened zirconia), carbides (silicon carbide and boron carbide), and nitrides (reaction-bonded, sintered, and pressure-densified silicon nitride). Monolithic ceramics are characterized by their complex microstructure, light weight, and stiffness, as well as resistance to high temperatures, corrosion, thermal shock, abrasion, and wear. Some of the major types of monolithic ceramics and their applications are shown in Table 2-2.

**Ceramic Coatings** — A ceramic coating can be applied to a substrate material to provide protection against the environment. Some ceramic coating techniques used today include plasma spray, high-velocity oxy-fuel (HVOF), flame spray ceramic coating, electron beam physical vapor deposition (EBPVD), and chemical vapor deposition (CVD). Coal-fired type ceramic coatings are used for lining vessels exposed to corrosive fluids. Thermal barrier coatings of zirconium oxide are used in the hot sections of military and commercial aircraft gas turbine engines, and are also being evaluated for utility-scale gas turbine engines and for drying rolls in the pulp and paper industry.

**Ceramic Composites** — Ceramic composites include matrix composites and continuous fiber ceramic composites (CFCCs), which are designed to produce a controlled failure by using ceramic fibers to carry the load across a developing crack. CFCCs are capable of withstanding extreme

conditions and can be tailored for operating in different process environments. Major applications for ceramic composites include cutting tools, aerospace and military, engines, wear and industrial materials, and bioceramics. Table 2-3 shows a number of applications being considered for ceramic composites.

**TABLE 2-2. MONOLITHIC CERAMIC APPLICATIONS**

<b>Monolithic Ceramics</b>	<b>Applications</b>
Silicon Nitride	Cutting tool inserts, diesel cam follower rollers, bearings, papermaking machine foils, wear parts, turbocharger rotors, manufacturing tooling, aircraft engine seal, fuel injector link, diesel glow plug, diesel prechamber, check valve balls, and slotted dewatering centrifuge liners for mining industry
Aluminum Oxide	Seal rings, rotary and gate valves, pump parts and liners, papermaking foils, suction box covers, palm guides, cyclone liners, liners in coal handling systems, wire drawing tool, thread guide in the chemicals and textile industries, chute and conveyor liners, precision surfaces for metrology, wear pads, chemical lab ware, molten metal fibers, mill liners and media, nozzles, pipes, and tubing liners
Silicon Carbide	Seals, thrust bearings, valves, pump parts, cyclone liners, radiant burners and heat exchanger tubes, high temperature liners such as in waste incineration, thermocouple protection tubes, links for high-temperature belt furnaces, bearings in magnetic drive and seal-less pumps, and grit-blast nozzle liners
Transformation-Toughened Zirconia	Tooling for production (or manufacture) of aluminum can, wire-drawing capstans, pulleys, rolls, guides, metal extrusion and other dies, slitter for cutting paper in papermaking machines, knife and scissor blades, hip replacements, golf cleats, and buttons

## 2.3 PROCESS DESCRIPTION

Advanced ceramics are processed in many different ways, but most include a few common processes. First, raw materials (such as oxides, nitrides, and carbides) are milled into fine powders. These powders are subjected to a greenning (forming) process. Greening, or green forming, is a method for shaping ceramics without using heat, where the properties of the green parts

**TABLE 2-3. APPLICATIONS BEING CONSIDERED FOR CERAMIC COMPOSITES**

<b>Ceramic Composites</b>	<b>Applications Being Considered</b>
Silicon Carbide Matrix CFCCs	Hot-gas recirculating fans, heat exchangers, gas-fired radiant burner screens, gas-fired radiant burner tubes, gas turbine engine combustion liners and tip shrouds, hot-liquid filtration, canned motor pump containment shells, gas-fired melting immersion burner tubes, and furnace pipe hangers
Alumina and Mullite Matrix CFCCs	Thermophotovoltaic burners/emitters, heat exchangers, hot-gas filtration, gas turbine engine combustion liners and shrouds, and burner stabilizers

(density, grain size, strength, etc.) determine the properties of the end product. The objective of the forming process is to create weak and temporary bonds that hold the ceramic particles together enough to be handled during subsequent processing.

The most common forming methods are:

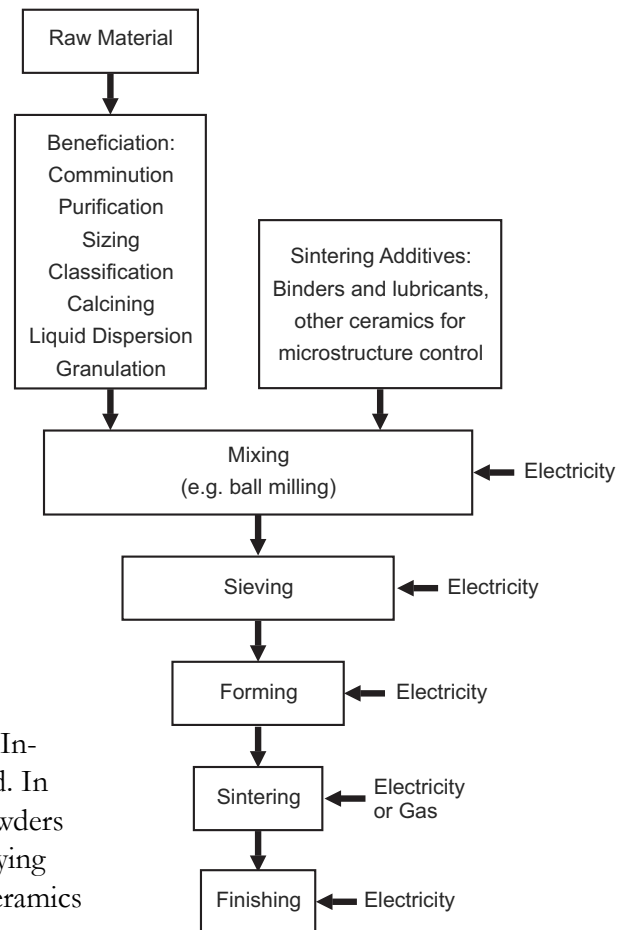
- Die pressing
- Slip casting
- Injection molding
- Extrusion
- Sol-gel molding

After forming, the ceramics are subjected to green machining to eliminate rough surfaces and seams, then dried through convection with heated air. A presintering thermal process is sometimes applied to provide additional drying and to decompose impurities prior to firing.

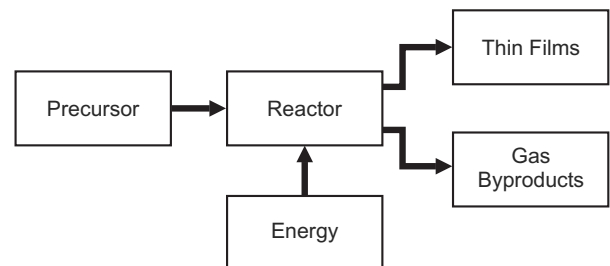
Some ceramics do not undergo the forming process. Instead, the ceramic powders are directly sintered or fired. In the sintering process, heat is applied to the ceramic powders (with or without pressure) with the objective of modifying the chemical composition of the ceramic. Advanced ceramics are usually fired in resistance-heated furnaces under controlled atmospheres. When the sintering process is complete, the parts are finished through machining, polishing, drilling, or grinding.

The production of composite ceramics follows the same steps described above, except reinforcements in the shape of particles, fibers, or whiskers are added in the forming stage. Figure 2-2 shows a basic process flow diagram for the manufacture of ceramic products.

**FIGURE 2-2. PROCESS FLOW DIAGRAM FOR ADVANCED CERAMICS PRODUCT MANUFACTURING**



**FIGURE 2-3. BASIC CHEMICAL VAPOR DEPOSITION FLOW DIAGRAM**



Ceramic coatings, such as those grown via deposition techniques, undergo a very different process than the one described above. For example, in the chemical vapor deposition technique, gaseous molecules (precursor) are transformed into a thin ceramic film deposited on the surface of a substrate. This technique, shown in Figure 2-3, occurs inside a chemical reactor. While the chemical vapor deposition technique is widely used in the semiconductor industry, it represents only one of the many different deposition processes used today.



## 2.4 ENERGY AND MATERIALS CONSUMPTION

Very little quantitative energy data exists for the advanced ceramics industry. Figure 2-2 shows the typical types of fuel inputs during each step of the production process. Most production stages are electrically powered, and sintering, the most energy consuming stage, can be either electrical or gas-fired. In most instances, gas firing takes place when the required sintering temperatures exceed 2,700°F, while electric firing is typically used for temperatures below 2,000°F.

Table 2-4 displays common sintering temperatures for various advanced ceramic applications, though firing cycle duration must also be considered an important variable. A 3,100°F firing cycle typically runs for 96 hours, with a six-hour hold at the top temperature. Similarly, a 2,400°F firing cycle takes 56 hours with a six-hour hold. Capacitors are electrically fired for 48 hours with a four-hour hold.

**TABLE 2-4. TYPICAL SINTERING TEMPERATURES FOR VARIOUS CERAMIC SUB-GROUPS**

Sub-Groups	Temperature, °F
Capacitors	1,650-2,400
Sensors & Actuators	2,400
Single Crystals - Saws	3,450
Fuel Cells - SOFC	2,400
Substrates	3,000
Spark Plugs	2,700
Electrical Insulators	2,700-2,900
Bearings	3,000
Zirconia	2,300-3,100
Misc.	2,700-2,900
Wear	2,700-3,100
Impact	2,700-3,100

SOURCE: KANIUK, PERSONAL COMMUNICATION, 2003.

Chemical vapor deposition energy sources include:

Thermal Energy

- Resistive heating - tube furnace
- Quartz tungsten halogen lamp - radiant heating
- Radio-frequency - inductive heating
- Laser (as a thermal energy source)

## Photo Energy

- UV - visible light
- Laser (as a photo energy source)

## 2.5 ENVIRONMENT

Environmental impacts caused by advanced ceramics tend to be negligible. Various air emissions are generated during the production of advanced ceramics. However, these are generally small. Similarly, effluents are mostly mild in nature and consist of wastewaters with insoluble ceramic raw materials.

### 2.5.1 AIR EMISSIONS

Various types of emissions are associated with each step of the production of advanced ceramics. Table 2-5 presents a summary of emissions for each production step.

**TABLE 2-5. AIR EMISSIONS DURING THE PRODUCTION OF ADVANCED CERAMICS**

Beneficiation	Mixing	Forming	Glazing	Firing	Finishing
PM-10 NOx SOx CO CO <sub>2</sub> VOC HCl	VOC	PM (dry forming only)	PM (metals and oxides) from glaze preparation	PM NOx SOx CO CO <sub>2</sub> HF	PM PM-10 VOC

SOURCE: ENVIRONMENTAL PROTECTION AGENCY, 1996.

During the beneficiation process, particulate matter smaller than 10 micrometers in diameter (PM-10) is generated. This particulate emission is the result of crushing, grinding, screening, classifying, handling, transferring, and storing the ceramic raw materials. Calciners also generate several forms of emissions, including PM, NOx, SOx, CO, CO<sub>2</sub>, and volatile organic compounds (VOCs). VOCs occur from incomplete combustion and volatilization of organic raw materials. Hydrochloric acid (HCl) emissions may result from leaching during the beneficiation process.

Mixing is generally a wet process, so PM emissions are not a factor in this particular stage. However, VOC emissions from the volatilization of binders, plasticizers, and lubricants occur during this stage.

Forming can take place as either a wet or dry process. While emissions from wet forming are negligible, dry forming processes, such as grinding or punching, result in PM emissions. The glaze preparation process also results in PM emissions from mixing and grinding.

Ceramic heat treating processes such as drying, presintering, and firing result in the release of combustion products (i.e., NO<sub>x</sub>, SO<sub>x</sub>, CO, CO<sub>2</sub>), PM emissions consisting of metals and inorganic materials, and fluorine compound emissions. Emissions during this stage are dependent on fuel type, raw material constituents, and heating temperature. Ceramic raw materials contain fluorine in concentrations ranging from 0.01 to 0.2 percent. At firing temperatures close to 930 to 1,110°F, hydrogen fluoride (HF) and silicon tetrafluoride can form and be emitted. Various techniques exist to reduce HF emissions, as shown in Table 2-6.

**TABLE 2-6. FACTORS THAT REDUCE HYDROGEN FLUORIDE EMISSIONS**

<b>Factor</b>	<b>Process Control Technology</b>
Body chemistry	Use high lime raw materials or lime additions
Body and setting density	Employ higher density of body or setting pattern
Atmospheric water	Use low hydrogen contents fuels
Preheating rate	Increase above dehydroxylation temperature
Soak temperature	Minimize
Vitrification	Increase through use of sintering aids
Soak duration	Minimize
Kiln draft	Minimize
Kiln exhaust temperature	Minimize

SOURCE: D. BROSNAN, 1992.

Finishing processes, such as grinding and polishing, result in dust emissions (PM, PM-10), while surface coating, annealing, and chemical treatment can emit VOCs.

Other efforts to control emissions include fabric filters, wet scrubbers, and electrostatic precipitators (ESPs) for PM emissions, and afterburners for VOC emissions.

Volatile gas products formed during the chemical vapor deposition process for ceramic coatings are seldom recycled because most of these byproducts do not have uses today. However, these gases are frequently hazardous and must be treated before being released to the environment.

### **2.5.2 EFFLUENTS**

Wastewaters result from the grinding, molding, glazing, and washing processes. Common techniques adopted to minimize wastewaters include using vacuums and damp brooms to clean dust from mixers and grinders (thereby reducing the amount of wastewater) and adopting water recirculation strategies. Wastewaters are mainly contaminated with mineral-based raw materials, many of which have low solubility levels and are visible in the effluent stream as suspended particles.

Table 2-7 shows typical water input of the slurry used for making slip or body for various advanced ceramics sub-groups. All input waters are evaporated during the production process.

### 2.5.3 WASTES, RESIDUALS, AND BY-PRODUCTS

Wastes and residuals are produced in the form of sludge, solid scrap from finishing processes, and rejected parts. Rejected rates can be high because of the tendency for micro-crack formation due to the brittleness of advanced ceramics. Table 2-8 shows typical scrap rates for various advanced ceramic products. Wastes are usually disposed of at high cost in landfills.

## 2.6 TARGETS OF OPPORTUNITIES FOR IMPROVED ENERGY & RESOURCE EFFICIENCY

In 1999, the United States Advanced Ceramics Association and the U.S. Department of Energy developed the *Advanced Ceramics Technology Roadmap*, which identifies the needs of OEMs and end-users and establishes the R&D necessary to widen the acceptance and potential of advanced ceramics. Table 2-9 summarizes the R&D needed to address the challenges of each of the main advanced ceramics categories identified in the roadmap.

The use of advanced ceramics has not yet reached its potential. Manufacturers and end-users are in constant search of materials that could improve their products and applications, but many users are concerned with the reliability, high costs, and properties of advanced ceramics as well as the limited amount of design and test experience with these materials.

New ceramic materials are currently being developed to increase the combustion efficiency of automobiles and aircrafts, thereby decreasing fuel consumption. Among the energy-efficient applications of advanced ceramics are solid oxide fuel cell tubes, ceramic thermal barrier coating systems, high-efficiency gas turbines, superconductors, and microturbines. Advanced ceramics are also used to encapsulate radioactive wastes and corral oil spills.

**TABLE 2-7. TYPICAL PERCENTAGES OF WATER USAGE BY SUB-GROUP**

Sub-Groups	% Water Usage
Capacitors	25
Sensors and Actuators	25
Fuel Cells - SOFC	25
Substrates	25
Spark Plugs	30
Electrical Insulators	30
Bearings	30
Zirconia	30
Miscellaneous	30

SOURCE: J. KANIUK, PERSONNEL COMMUNICATION, 2003.

**TABLE 2-8. TYPICAL PERCENTAGE SCRAP RATE BY SUB-GROUP**

Sub-Groups	% Scrap
Capacitors	3
Fuel Cells SOFC	20
Substrates	3
Spark Plugs	3
Electrical Insulators	5
Bearings	5
Zirconia	10
Misc	10
Wear	5
Impact	5

SOURCE: J. KANIUK, PERSONNEL COMMUNICATION, 2003.

**TABLE 2-9. ADVANCED CERAMICS INDUSTRY R&D NEEDS**

<b>Key Challenges</b>	<b>Priority and R&amp;D Needs to Address the Challenge</b>
<b>Monolithic Ceramics</b>	
Improve resistance to fracture	<ul style="list-style-type: none"> <li>● Increased material toughness</li> <li>● Increased material strength</li> <li>● Improved design methods/practices</li> <li>● Lower stress designs</li> </ul>
Improve resistance to the use environment (e.g., oxidation, corrosion)	<ul style="list-style-type: none"> <li>● Improved material chemical stability</li> <li>● Improved protective coatings</li> <li>● Improved functional gradient construction</li> <li>● Improved resistance to contact stress</li> </ul>
Increase reliability	<ul style="list-style-type: none"> <li>● Reduced material variability through improved fabrication process and control</li> </ul>
Reduce the cost of manufacturing	<ul style="list-style-type: none"> <li>● Lower-cost powders/precursors</li> <li>● Quantity scale-up</li> <li>● Increased automation</li> <li>● Decreased final machining</li> <li>● Lower cost quality assurance</li> <li>● Rapid prototyping integrated into manufacturing</li> </ul>
<b>Ceramic Matrix Composites</b>	
Reduce the cost of precursors	<ul style="list-style-type: none"> <li>● Reduced scale-up cost of fiber manufacturing</li> <li>● Lower-cost interface materials and deposition processes</li> </ul>
Improve understanding of failure modes	<ul style="list-style-type: none"> <li>● Basic scientific understanding of interactions between CMC constituents and application environments</li> <li>● Micro-and-macro mechanics understanding of interactions of CMC with an applied stress or strain</li> </ul>
Increase temperature stability to 1,200-1,500°C	<ul style="list-style-type: none"> <li>● Higher-temperature fibers, matrix materials, and interface coatings</li> <li>● Environmental barrier coatings (EBCs)</li> <li>● Active cooling designs</li> </ul>
Manufacturing scale-up and cost reduction	<ul style="list-style-type: none"> <li>● Larger furnace design and construction</li> <li>● Automation/semi-automation of preform fabrication</li> <li>● Low-cost tooling</li> <li>● Near-net-shape fabrication</li> <li>● Low-cost in-process and post-process quality assurance</li> </ul>
<b>Ceramic Coating Systems</b>	
Improve coating adhesion to substrate	<ul style="list-style-type: none"> <li>● Improved pre-coating surface treatments</li> <li>● Improved interlayers</li> <li>● Functional gradation</li> </ul>
Improve understanding of failure modes and mechanisms	<ul style="list-style-type: none"> <li>● Basic scientific understanding</li> <li>● Micro-and-macro mechanics understanding</li> </ul>
Improve coating and system properties	<ul style="list-style-type: none"> <li>● Improved abrasion resistance to 10 times better than chromium at half the cost</li> <li>● Tribological coatings that require minimal liquid lubrication</li> <li>● Low thermal conductivity thermal barrier coatings</li> </ul>

SOURCE: *ADVANCED CERAMICS TECHNOLOGY ROADMAP*, 2000.

# 3. CARBON PRODUCTS

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## 3.1 INDUSTRY OVERVIEW

The carbon products industry is a diverse, cross-cutting industry supplying critical materials and components to some of the United States' most essential industries, such as aluminum, steel, chemicals, aerospace, and electronics, as well as recreation and environmental protection. Carbon products are available as end products such as golf club shafts, activated carbon filters, and components of rubber compounds, while other carbon products, such as carbon anodes, are consumed as essential components in the production of such commodity materials as aluminum and steel.

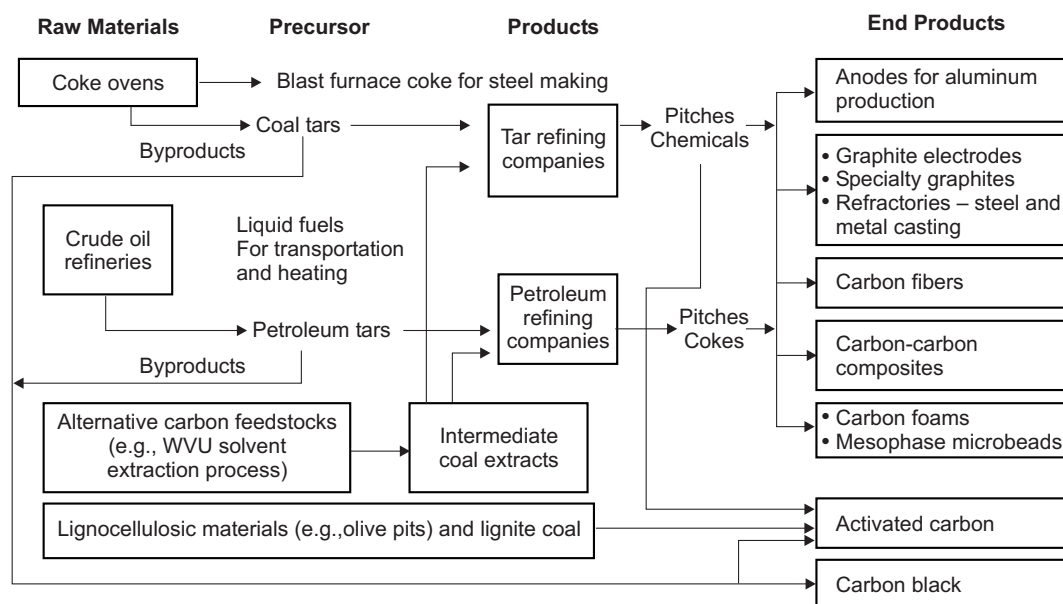
Elemental carbon occurs naturally in either its crystalline (more ordered) or amorphous (less ordered) form. Essentially, any organic material can be thermally transformed to carbon. The carbonization process uses heat to convert organic precursors into a carbon polymer. Elemental carbon is transferred on a global scale from one process to the next on its way to final applications. A large portion of the carbon products industry is built on recovering and processing byproducts from other primary operations.

In its many varying manufactured forms, carbon can exhibit a wide range of electrical, thermal, and chemical properties controlled by the selection of raw materials and thermal processing during manufacture. Differences in properties of the final carbon products depend on the raw materials used, the extent of completion of overall chemical and physical ordering processes, and whether the thermal transformation takes place in the vapor, liquid, or solid phase. Carbon products can be grouped according to the extent of material processing: raw material, carbon precursors, and finished carbon products. Figure 3-1 presents an overview of the processing flow from raw material to finished carbon product.

## 3.2 INDUSTRY PERFORMANCE AND MARKET TRENDS

Although two NAICS codes are exclusive to only carbon products, official government statistics for carbon products fall across several NAICS codes. Available information on shipments, employment, and other measures for these two NAICS codes are depicted in Table 3-1 (DOC 2003). The trend in shipments in these categories since the inception of the NAICS classification system in 1997 is shown in Figure 3-2.

Beyond these official statistics, estimated economic statistics as of the mid-to-late 1990s have been compiled for many intermediate and final carbon

**FIGURE 3-1. OVERVIEW OF CARBON PRODUCTS PROCESS FLOW**

products. For current applications, Table 3-2 lists approximate price, volume, and market projections for carbon feedstocks. Table 3-3 lists similar information for major current carbon products.

**TABLE 3-1. 2001 CARBON PRODUCTS GOVERNMENT DATA**

	<b>Carbon Black</b>	<b>Carbon and Graphite Product Manufacturing</b>
NAICS Code	325182	335991
Value of Shipments	\$1 billion	\$1.8 billion
Employment	1,761	9,174
Capital Expenditures	\$35.8 million	\$57.7 million
Purchased Energy	749 million kwh	1.275 billion kwh
	Not available	\$98 million \$54.2 million for electricity \$43.9 million for fuels
Exports	\$167 million	\$504 million
Imports	\$138 million	\$385 million
Trade Balance	\$29 million	\$119 million

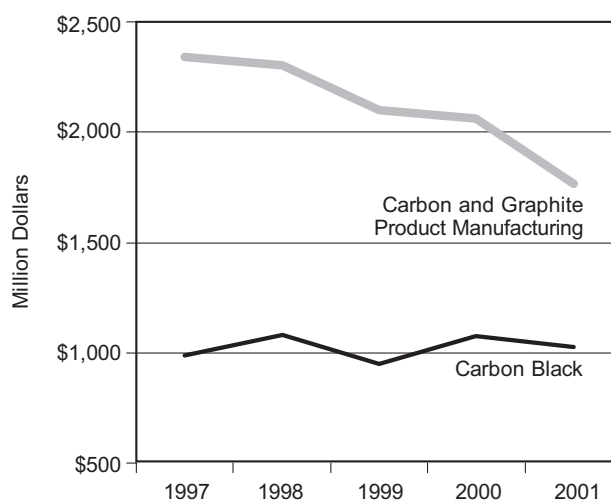
SOURCE: DEPARTMENT OF COMMERCE, ANNUAL SURVEY OF MANUFACTURES 2001.

### INDUSTRY STRUCTURE

Relatively few carbon products producers exist in the United States. High capital equipment and facility costs tend to limit the number of companies that can produce raw materials and carbon precursors. Greater diversity can be found in the finished products sector, where a greater number of smaller manufacturers and fabricators supply specialized carbon products to different markets.

In the late 1980s and early 1990s, contraction occurred within the carbon products industry. Companies merged with their competitors or suppliers, purchased idled capacities, or even exited the business entirely. This consolidation continues today, to a lesser extent, in more mature market segments. U.S. companies have also shifted some of their operations offshore to control operating costs and follow the shifts in operations of certain heavy industries (such as steel making and chemical production) which are principal markets for many of the suppliers of raw material and carbon precursors. Activated carbon was an exception; production of activated carbon increased in the United States during the 1990s, and producers have not yet shifted operations offshore (*Carbon Products Vision*).

FIGURE 3-2. CARBON PRODUCTS SHIPMENT TRENDS



SOURCE: ASM, INTERNATIONAL.

Industry structure tends to fall along the following product lines:

**Raw materials** — Coal tars and petroleum tars, the raw materials for most carbon products, are sold as byproducts of other operations such as the refining of crude oil for fuels and the making of blast furnace coke

TABLE 3-2. INTERMEDIATE CARBON PRODUCTS SUMMARY

Product	Feedstock	Domestic Annual Sales	Worldwide Annual Sales	Status and Projection
Anode Coke	Petroleum tar, coal tar	2.0 million tons (\$400 million)	8.0 million tons (\$1.6 billion)	Declining quality of petroleum tar due to high levels of sulfur and vanadium in imported crude oil; 4% annual increase in demand will result from growth in aluminum production
Carbon Black	90% Petroleum tar, 10% coal tar	1.5 million tons (\$450 million)	7.0 million tons (\$1.8 billion)	Varies with vehicle part and vehicle production cycles; net world-wide growth projected at 2-3% annually
Binder Pitch	Coal tar from coke ovens	0.9 million tons (\$175 million)	1.5 million tons (\$525 million)	Supply of coal tar declining due to changes in steel processing
Needle Coke	Petroleum tar, coal tar	0.4 million tons (\$160 million)	1.3 million tons (\$550 million)	Mature with growth of about 1-2% annually
Impregnating Pitch	Petroleum tar	0.2 million tons (\$50 million)	0.4 million tons (\$95 million)	Adequate for demand

SOURCE: CARBON PRODUCTS VISION.



**TABLE 3-3. FINISHED CARBON PRODUCTS SUMMARY**

Product	Feedstock	Domestic Annual Sales	Worldwide Annual Sales	Status and Projection
Carbon Anodes	Calcined coke, binder pitch	1.6 million tons (\$500 million)	7.5 million tons (\$2.3 billion)	3-4% annual growth in world-wide aluminum production will support sustained growth.
Graphite Electrodes	Needle coke, binder pitch, impregnating pitch	0.4 million tons (\$1.0 billion)	1.1 million tons (\$2.8 billion)	Slow growth in demand due to improved efficiencies but growing emphasis on electric air furnaces.
Activated Carbon	Various organic precursors, including coal and cellulose material	0.2 million tons (\$415 million)	0.55 million tons (\$1.2 billion)	Excellent growth potential for air and water purification applications resulting from tighter environmental regulation and sustainable development.
Specialty Graphite	Cokes, binder pitch, impregnating pitch	30,000 tons (\$200 million)	200,000 tons (\$1 billion)	New applications such as fine grain specialty graphites will expand sales.
Carbon Fibers and Composites	PAN, CTP, Carbon fibers and matrix pitch	8,000 tons (\$490 million)	14,000 tons (\$950 million)	Cyclical aerospace demand drives market.

SOURCE: CARBON PRODUCTS VISION.

for steel production. The raw material supply for the carbon industry is therefore subject to events and conditions in other primary markets. This situation is undesirable, and companies and organizations dependent on quality materials support researching alternate supply sources (e.g., solvent extraction processes to produce aromatic polymer precursors directly from coal, coal tar, and petroleum tar combinations, as well as anthracite and epoxy resin developed in Norway).

**Carbon black** — In 1998, approximately 3.6 billion pounds of carbon black were produced in the United States. The major markets for carbon black include rubber reinforcement for automotive uses (64 percent); industrial rubber uses (18 percent); black pigment for inks, coatings, plastics; and exports. The carbon black industry experienced significant consolidation in the 1980s as a result of the automotive industry's switch to radial tires and the subsequent increase in miles driven per tire. Today, there are six major suppliers to the U.S. market; of these, three account for nearly 60 percent of worldwide production. A number of domestic suppliers also exist because carbon black is relatively inexpensive and very bulky, limiting shipping distance. Economies of scale in this industry lie in commercial relationships, technology development, and technology optimization, as opposed to size of scale for individual plants, which is logistically limited.

**Carbon precursors** — Producers of carbon precursors process coal and petroleum tars into a range of chemical products including pitches, cokes, and monomers for making engineered plastics. These companies are generally large, multinational chemical concerns producing materials on a commodity basis. In many cases, these companies have corporate ties or other strong relationships with raw materials suppliers. For example, Conoco, Inc. manages refining operations that produce raw tars, and runs coking and calcining facilities that make carbon product precursors.

**Finished products** — Companies making finished carbon products are more closely aligned with their customers. Operations are organized around particular products or services, with investments directed more toward processing technologies and new product development. These companies are closest to the end users of carbon products and are often more visible to suppliers and customers than to the general public.

## OUTLOOK

Demand is projected to increase as a result of new applications for carbon products and steady growth in existing applications. Market growth for carbon products is strongest for the value-added segment of the industry. New and emerging applications for carbon products include consumer electronics such as heat sinks for high-density computer chips; activated carbon filters and beds to clean various air emissions and aqueous streams; carbon materials for batteries, fuel cells, and other energy storage devices such as flywheels; surface transportation applications such as lightweight chassis components for highly efficient vehicles; and civil infrastructure applications for repair and retrofit of buildings and bridges. Additional growth for carbon products will result from environmental pressures to reduce greenhouse emissions and improve water quality, and to reduce evaporative emissions from automotive engines. Companies are also finding additional applications for higher-value carbon products and are developing new carbon products that sell for tens to hundreds of dollars per pound. These high-value products take advantage of unique properties of carbon materials to offer customers superior performance on existing or new applications (*Carbon Products Vision*).

Two conflicting trends will affect the structure of the carbon products industry in the future. In more mature markets, companies are consolidating and merging to maximize return on capital. At the same time, new companies are forming and spinning off to follow new markets for carbon products in areas such as reinforcement of buildings and bridges. Globalization will also influence industry structure by driving manufacturing operations to developing countries. Key drivers include:

- Increasing globalization of the economy will generate new markets, move manufacturing offshore, tighten supply of raw materials, increase demand for carbon-consuming products such as aluminum and activated carbon, and cause increased cost pressures
- Increases in imported feedstocks will result in lower-quality precursor materials, higher costs for raw materials, and demand for alternate material forms
- Aggressive environmental policies will generate demand in end-use areas such as efficient transportation systems, water purifiers, and more efficient energy-intensive processes such as electric-arc furnaces
- Worldwide pitch and coke requirements for the aluminum industry are projected to more than double by 2020

### 3.3 PROCESS DESCRIPTION

Coal tars and petroleum cokes are the principal raw materials used in the carbon products industry. These materials are byproducts of petroleum refining and other coal and oil processing operations. In the United States, approximately 1.8 million metric tons of coal tar and 24 million metric tons of petroleum coke are produced each year (the United States accounts for approximately seven percent of worldwide petroleum coke production).

Pitches and cokes, derived from coal and petroleum tars or heavy aromatic liquids, are the two main carbon precursor materials used in the production of bulk carbon and graphite products and in the manufacture of carbon blacks. Pitches have a glass-like character while cokes are infusible solids. Bulk carbon and graphite products (such as electrodes) are produced by first blending calcined coke as a filler and liquid pitch as a binder, then processing this “green” material through a series of progressively higher temperatures to achieve the desired properties.

Petroleum coke is the largest single precursor material in terms of quantity for manufactured carbon and graphite products; approximately 10 million tons were consumed worldwide in 1997 (*Carbon Products Vision*). Other precursors include natural graphite, hydrocarbon gases, anthracite, synthetic resins and carbon blacks. Carbon blacks are nanoscale carbon particulates produced by pyrolysis of feedstocks from the vapor phase with homogeneous nucleation of solid carbon.

#### PETROLEUM COKE AND CARBON ANODES

The major ingredient in carbon anodes is petroleum coke. A number of different cokes with varying sulfur contents are used in anode production. Petroleum coke is typically calcined in a rotary kiln at temperatures between 2,300 and 2,650°F. To avoid airburning once it exits the kiln, the coke is usually sprayed with water to reduce its temperature to approximately 200°F. Depending on the dissolved solids content of the quenching water, varying

amounts of impurities can remain on the coke. The properties of the calcined coke have a significant effect on anode properties and on carbon consumption.

Two types of carbon anodes may be used during the reduction process – anode paste or pre-baked anode. The anode paste plant or “green mill” produces anode paste or briquettes for Soderberg cells, and green pressed anodes (which are subsequently baked in an anode furnace) for prebake cells. Seventeen of the primary aluminum plants in the United States use prebaked anodes; the other six use anode paste. In the prebake process, multiple anodes are formed and baked prior to their use in reduction cells. These prebaked blocks, each of which may weigh up to 1 ton, must be replaced after two to three weeks of service (EPA, 1995). A large smelter will consume several thousand anode blocks each week. In the Soderberg process, a single mass of paste or briquettes forms the anode. Because the anode is baked in situ in the reduction cell, separate anode bake furnaces are not required.

Additional discussion of anodes is included in Chapter 3 (Anode Production) of the *Energy and Environmental Profile of the U.S. Aluminum Industry*.

### **CARBON BLACK**

Carbon black is generally manufactured in a special furnace by pyrolysis of aromatic refinery oil with heat supplied by natural gas combustion. The formation of this highly aromatic structure takes place at approximately 2,550°F using carbon from both the refinery oil and the natural gas. Primary quench water cools the gases to 900°F to stop the reaction. The exhaust gases entraining the carbon particles are further cooled to approximately 450°F by passage through heat exchangers and direct water sprays. The black is then separated from the gas stream, usually by a fabric filter. The recovered carbon black is finished to a marketable product by pulverizing and wet pelletizing to increase bulk density. Water from the wet pelletizer is driven off in a rotary dryer. The dried pellets are then conveyed to bulk storage. Process yields range from 35 to 65 percent, depending on the feed composition and the grade of black produced.

### **OTHER CARBON PRODUCTS**

Activated carbon manufacturing consists of a charring or carbonization step in which most of the non-carbon material is volatilized by pyrolysis (usually between 900 and 1,400°F). A fine pore structure is then formed using an activation process, either by oxidizing gases or chemicals which corrode the carbon.

Carbon fiber manufacture follows a basic sequence involving spinning, stabilization, carbonization, and application of a finish or sizing to facilitate

handling. The specific processing details are different for each type of precursor (e.g., polyacrylonitrile, pitch, or rayon).

### 3.4 ENERGY AND MATERIALS CONSUMPTION

Producing carbon products requires considerable amounts of energy, the cost of which is often a significant portion of the total cost for a carbon product. Table 3-4 provides a summary of estimated energy consumption for the carbon products industry.

**TABLE 3-4. CARBON PRODUCTS ENERGY CONSUMPTION\***

Carbon Product	Specific Energy Use (Btu/lb)	Annual Energy Use (trillion Btu)
Anode Coke	1,750	7
Carbon Black	12,000	43
Graphite Electrodes	60,000	48
Specialty Graphites	60,000	7
Carbon-Carbon Materials	1,700,000	2
Total		107

\* EXCLUDES EMBODIED ENERGY

### COKE, PITCH, AND CARBON ANODES

Table 3-5 presents energy requirements for manufacturing the coke and pitch used in anodes, and the process energy requirements of anode production itself in terms of energy per ton of anode and energy per ton of primary aluminum. The specific process energy requirements for anode production are estimated to be 3.5 million Btu per ton. Approximately 2 million tons of anode coke are produced each year in the United States, consuming roughly 7 trillion Btu each year.

**TABLE 3-5. PROCESS ENERGY USE IN COKE, PITCH, AND ANODE PRODUCTION**

Energy Source	Coke Production	Pitch Production	Anode Production	Total Specific Energy Use per Ton of Aluminum
	10 <sup>6</sup> Btu/ton of coke	10 <sup>6</sup> Btu/ton of pitch	10 <sup>6</sup> Btu/ton of anode	10 <sup>6</sup> Btu/ton
Electricity	0.11	--	1.59	0.72
Natural Gas	2.45	0.26	1.34	0.60
Distillate Oil	1.04	0.10	0.29	0.13
Propane and LPG	--	--	0.29	0.13
NET TOTAL	3.60	0.36	3.51	1.58

SOURCE: ENERGY AND ENVIRONMENTAL PROFILE OF THE U.S. ALUMINUM INDUSTRY.

A substantial percentage of the total energy used in the anode baking process comes from the anode binder pitch (EPA, 1996). Very little energy is needed to produce anodes for Soderberg cells. Anode paste briquettes are primarily dried with their residual enthalpy (Richards, 1997).

### **CARBON BLACK**

Production of carbon black requires approximately 12,000 Btu per lb of carbon black obtained. This level of process energy consumption equates to approximately 43 trillion Btu per year, based on an estimated 1998 production of 3.6 billion pounds. The feedstock energy costs are approximately 40,000 Btu per lb of carbon black, which is equivalent to 144 trillion Btu per year. Total energy consumption, including embodied energy, is approximately 52,000 Btu per lb, or 187 trillion Btu per year (Battelle, 1994).

### **OTHER CARBON PRODUCTS**

Approximately 120 million Btu per ton are consumed annually in the production of graphite electrodes for use in electric arc furnaces. Assuming 400,000 tons per year domestic production, approximately 48 trillion Btu are consumed annually in production of graphite electrodes. Similarly, the annual U.S. production of approximately 30,000 tons of specialty graphites consumes approximately 8 trillion Btu of energy through baking and graphitizing operations (*Carbon Products Vision*).

Energy use accounts for approximately 10 percent of the per pound cost for carbon-carbon materials. Approximately 1.7 million Btu are required to produce 1 pound of carbon-carbon material. Approximately 600 tons of carbon-carbon are produced each year in the United States, requiring approximately 2 trillion Btu per year. Nearly all of the energy for making carbon-carbon materials comes from natural gas. Table 3-6 summarizes key energy and environmental facts for the carbon products industry.

**TABLE 3-6. KEY ENERGY AND ENVIRONMENTAL FACTS - CARBON PRODUCTS**

<b>Annual Energy Consumption</b>	<b>Emissions</b>	<b>Effluents</b>	<b>Byproducts</b>
<ul style="list-style-type: none"> <li>• 7 trillion Btu for carbon anodes</li> <li>• 43 trillion Btu for carbon black</li> <li>• 48 trillion Btu for graphite electrodes</li> <li>• 7 trillion Btu for specialty graphites</li> <li>• 2 trillion Btu for carbon-carbon materials</li> </ul>	<ul style="list-style-type: none"> <li>• Largest source - high-temperature processing</li> <li>• Carbon monoxide</li> <li>• Particulates</li> <li>• Organic compounds</li> <li>• Fluorides</li> <li>• Polycyclic organic matter</li> <li>• SO<sub>2</sub></li> <li>• NO<sub>x</sub></li> </ul>	<ul style="list-style-type: none"> <li>• Largest source - wet air pollution control technologies</li> <li>• Typical process water volume - 6,430 lb/ton of anode produced</li> </ul>	<ul style="list-style-type: none"> <li>• Carbon dust</li> <li>• Burn-offs</li> <li>• Refractory bricks</li> </ul>

### 3.5 ENVIRONMENT

The carbon products industry generates a variety of emissions, effluents, and byproducts during manufacture.

#### 3.5.1 Air Emissions

Overall air emissions for the two industry-specific NAICS codes are depicted in Table 3-7. Specific emissions by process are described in more detail below.

**TABLE 3-7. 1999 CARBON PRODUCTS INDUSTRY EMISSIONS (TONS)**

Pollutant	Carbon Black (NAICS 325182)	Carbon and Graphite Products (NAICS 335991)
Sulfur Dioxide	53,598	3,043
VOCs	32,880	640
NO <sub>x</sub>	7,826	535
Carbon Monoxide	889,261	20,103
Particulate Matter-10 (PM10)	2,579	1,245
Particulate Matter-2.5 (PM2.5)	2,086	947

SOURCE: EPA WEBSITE, FACILITY SIC REPORT.

#### COKE AND ANODE MANUFACTURE

Most air emissions associated with anode manufacturing are generated during anode baking. Emissions from anode bake ovens include:

- High boiling organics (from the cracking, distillation, and oxidation of paste binder pitch)
- SO<sub>2</sub> (from the sulfur in carbon paste, primarily from the petroleum coke)
- Fluorides (from recycled anode butts)
- Other particulate matter
- CO<sub>2</sub> and other products of fuel combustion

Concentrations of uncontrolled SO<sub>2</sub> emissions from anode baking furnaces range from 5 to 47 parts per million (based on three percent sulfur in coke) (EPA, 1995a). In addition to anode baking, air emissions are generated during anode paste mixing, transfer, and anode forming. These emissions include coke fines, particulate matter, and organic compounds.

The hydrogen fluoride (HF) and polycyclic organic matter (POM) emitted from the anode bake furnace stack are designated by EPA as hazardous air pollutants (HAPs). Anode bake furnaces emit approximately 700 tons per year of total fluoride (TF), the vast majority of which is gaseous or hydrogen fluoride from uncontrolled bake furnaces (EPA, 1996a). Hydrogen fluoride emissions result from the recycling of anode butts (fluorides not removed

during cleaning of the butts are volatilized in the furnace and removed with the flue gas stream). The amount of HF emitted depends on the quantity of anode butts recycled, the cleanliness of the butts, and the efficiency of the emission control device, if any are used (EPA, 1996a). Fluorides also evolve in the furnace, originating from residual bath materials that adhere to the recycled anode butts. Because of residual moisture and elevated temperatures in the furnace, most of the fluoride that is evolved (approximately 95 percent) is hydrogen fluoride (EPA, 1996).

The amount of particulate matter emitted can vary widely depending on the type of furnace, fuel used, and other factors. The particulate matter released consists mainly of condensed tar attached to dust released through openings in the oven brickwork, or from the placement and removal of packing coke (EPA, 1996a).

Emissions of polycyclic organic matter (POM) originate from the coal tar pitch used as the binder and evolve as the green anode is baked in the furnace. POMs are also generated during the production of Soderberg anode paste.

Anode bake furnaces emit approximately 550 tons of POM annually, measured as methylene chloride extractables (EPA, 1996a). Tests at two bake furnaces showed that the 20 targeted POM compounds were generated at a rate of 0.3 to 0.9 lb per ton of anode prior to control by dry alumina scrubbers. Total annual POM emissions from U.S. paste production plants have been estimated at 147 tons (EPA, 1996a).

The coke calcination process generates sulfur emissions, which are released with volatile matter during thermal devolatilization. Sulfur is also lost or burned in association with coke entrainment or combustion in the kiln coke bed and in the kiln exhaust. Additional sulfur is thermally dissociated from the coke during calcination (Garbarino and Tonti, 1993).

Table 3-8 lists process-related emission factors for coke and anode production. The first set of factors for anode production was calculated as part of a 1991 survey of 11 North American smelters. These factors represent weighted average factors from actual plants with various emissions control technologies. The coke production emission factors were also calculated from this survey. The second set of data for anode production is the result of a 1994 survey of 27 European smelters.

A variety of methods are used to control emissions during anode production. Allowable emission factors for anode baking furnaces are shown in the *Energy and Environmental Profile of the U.S. Aluminum Industry*.



**TABLE 3-8. TYPICAL EMISSION FACTORS FOR COKE AND ANODE PRODUCTION (LB/TON OF ANODE)**

Pollutant	Amount		
	Coke Production	Anode Production	
		N. American Survey <sup>a</sup>	European Survey <sup>b</sup>
Particulate	0.80	1.26	0.3 <sup>c</sup>
SO <sub>x</sub>	1.62	1.40	1.80
NO <sub>x</sub>	0.36	0.32	0.48
CO	0.74	0.50	NA
CO <sub>2</sub>	0.00	0.00	NA
Organics	0.58	0.40	0.12 <sup>d</sup>
Fluorides	0.0008	0.50	0.20

NA Data not available

<sup>a</sup> Weighted average composite values from 11 N. American smelters participating in a 1991 survey

<sup>b</sup> Weighted average composite values from 27 European smelters participating in a 1994 survey

<sup>c</sup> Reported as dust

<sup>d</sup> Reported as polycyclic aromatic hydrocarbons (PAH)

SOURCES: DATA REPORTED BY NOLAN RICHARDS, 1997. (NOTE: THE DATE REFERS TO THE RELEASE OF THE INFORMATION, SOME OF WHICH WAS DEVELOPED IN 1991.) 1994 ENVIRONMENTAL SURVEY FOR ELECTROLYSIS PLANTS, PRESENTED AT POLLUTION PREVENTION IN THE ALUMINUM INDUSTRY, SPONSORED BY THE ALUMINUM ASSOCIATION, NOVEMBER 1995.

## CARBON BLACK

Carbon black emissions include particulate matter, carbon monoxide, organics, nitrogen oxides, sulfur compounds, polycyclic organic matter, and trace elements. Gaseous emissions may vary considerably for different grades of carbon black. Effluents from facilities are regulated by EPA with special attention given to the release of fine particles that carry aromatic hydrocarbons. OSHA has special guidelines for carbon black in view of its fine particle size and association with higher aromatic hydrocarbons. Carbon black is classified as a possible carcinogen. The permissible exposure limit is 3.5 mg/m<sup>3</sup>. Fugitive dust emissions from vents on storage bins, bagging operations, and bulk loading of railroad cars are also a concern in the handling of carbon black.

### 3.5.2 EFFLUENTS

Effluents are generated during the manufacture of anodes. Prior to baking, the warm, green anode blocks are conveyed in a tank of cold water that cools them and reduces deformation. This water has to be either recycled or treated and released. Lime-sand treatment is generally used to remove traces of organics (Richards, 1997).

The net process water consumption for anode production (excluding fuel-related water use) is estimated at 6,430 pounds per ton of anode (Richards,

1997). Table 3-9 shows estimated average levels of total suspended solids, fluorides, and organics contained in typical anode manufacturing process wastewater based on the 1991 survey.

### WASTES, RESIDUALS, AND BYPRODUCTS

The production of carbon anodes generates several byproduct streams containing carbon contaminated with electrolyte materials. Most of these byproduct streams are recycled for anode carbon production or other uses, and only a few are disposed of as waste.

During anode baking, approximately 35 percent of the pitch is volatilized. At plants with electrostatic precipitators (ESPs), the major part of uncombusted volatiles is collected as tar. The collected tar may amount to 4-8 pounds per ton of baked anodes, depending on the combustion efficiency. Traditionally, the tar is deposited, recycled during carbon block production, or combusted (Foosnaes et al., 1994). Waste tar combustion systems allow ESP tar to be used as a fuel, substituting for oil or gas in the anode baking furnace.

A worldwide survey sponsored by the Aluminum Committee of the Minerals, Metals, & Materials Society found that carbonaceous waste materials from prebaked anode production are generated on the order of 28 pounds per ton of aluminum produced. Refractory wastes from anode baking furnaces are on the order of 22 pounds per ton of aluminum (Keller, 1994). A certain amount of the carbonaceous wastes from anode manufacturing is recycled in the process. However, evidence shows that petroleum coke and pitch quality will deteriorate in the future, making recycling less acceptable for disposal of carbon wastes (Keller, 1994).

Byproducts from anode manufacturing, including several sources of carbon dust, are depicted in more detail in Section 3 of the *Energy and Environmental Profile of the U.S. Aluminum Industry*.

**TABLE 3-9. TYPICAL ANODE MANUFACTURING EFFLUENTS**

Pollutant	Quantity (lbs per 10 <sup>6</sup> lbs)
Fluoride	4.8
Total Suspended Solids	3.9
Organics	5.0

SOURCE: DATA REPORTED BY NOLAN RICHARDS, 1997. (NOTE: THE DATE REFERS TO THE RELEASE OF THE INFORMATION, SOME OF WHICH WAS DEVELOPED IN 1991.)

### 3.6 TARGETS OF OPPORTUNITY FOR IMPROVED ENERGY & RESOURCE EFFICIENCY

Key opportunities for improved manufacturing technologies include:

- Continuous processing of carbon products
- Greater capture and reuse of heat, which would also improve energy efficiency
- Low-temperature processing of carbon materials as a greater long-term technology advancement with potential to significantly improve energy efficiency (*Carbon Products Vision*)



# 4. FORGING

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## 4.1 INDUSTRY OVERVIEW

Forging is the process of pressing, pounding, or squeezing malleable metals under great pressure to form high-strength parts known as forgings. The process refines the grain size and flow of the metal, thereby improving its structure and increasing its resistance to fatigue and impact. Some of the most common forged metals include: carbon alloys and stainless steels, very hard tool steels, aluminum, titanium, brass, copper, and high-temperature alloys that contain cobalt, nickel, or molybdenum.

According to the U.S. Census, the total number of commercial forging establishments is over 500 (83 percent iron and steel, 17 percent non-ferrous). In 2001, the industry employed a total of about 35,792 (Annual Survey of Manufacturers) employees, two-thirds in facilities processing iron and steel and the remainder in nonferrous facilities.

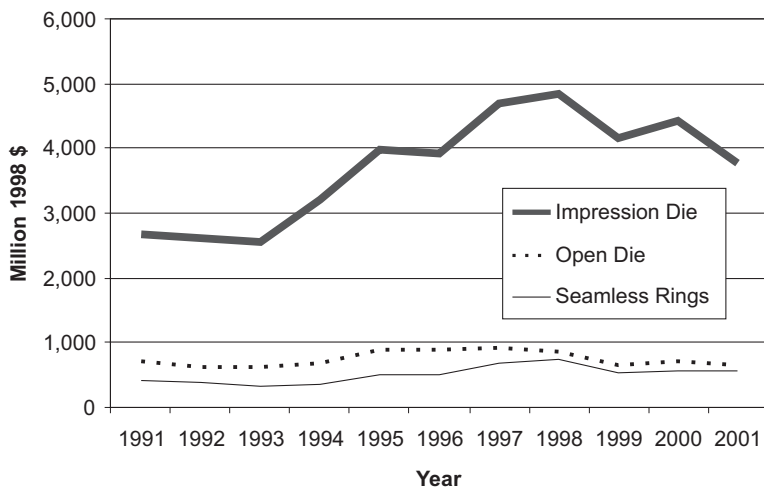
## 4.2 INDUSTRY PERFORMANCE AND MARKET TRENDS

The total value forging industry shipments in North America is believed to be in excess of \$6 billion, of which approximately 90 percent is represented by custom, made-to-order forgings. Under the Standard Industry Classification (SIC), forgings are covered by codes 3462 (iron and steel forgings) and 3463 (nonferrous forgings). The recently developed North American Industry Classification System (NAICS) catalogues iron and steel forgings and nonferrous forgings under NAICS codes 332111 and 332112, respectively.

### VALUE OF SHIPMENTS AND PRODUCTION

In 2001, industry shipments for the custom impression-die forging industry decreased by five percent from the previous year to \$4.46 billion. The automotive industry represented the largest market segment, accounting for 32 percent of all impression die sales, followed by aerospace applications at 31 percent. Shipments for the custom open-die forging industry increased by 2.4 percent from the previous year to \$763 million. Construction, mining, and materials handling remained the leading market for open-die forges at 15 percent of the total sales for this segment. The 2001 value of shipments for custom seamless rings increased by over 9 percent to \$662.6 million. Approximately 53 percent of seamless ring sales were attributed to aerospace engines and engine parts.

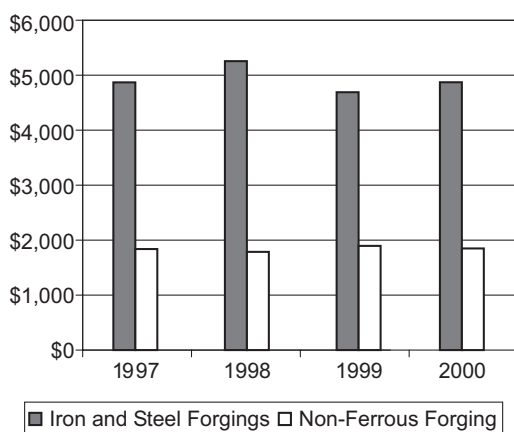
Over the last ten years, the value of shipments for custom impression-die forgings experienced the largest increase (60 percent), while shipments for

**FIGURE 4-1. CUSTOM ORDER FORGING INDUSTRY VALUE OF SHIPMENTS IN NORTH AMERICA (ENCOMPASSING ALL METALS FORGED IN MILLIONS OF 1998 DOLLARS)**

SOURCE: FORGING INDUSTRY ASSOCIATION 2001 ANNUAL FORGING INDUSTRY SALES RELEASED BY FORGING INDUSTRY ASSOCIATION: OPEN DIE/ROLLED RING FORGING SHIPMENTS IMPROVED; IMPRESSION DIE FORGING SLIPS, APRIL 15, 2002.

custom seamless ring forgings also increased considerably (51 percent). The value of shipments for custom open-die forgings experienced a modest 3 percent increase over the last ten years. Figure 4-1 shows a 10-year trend in the value of shipments for custom-order forgings.

Between 1997 and 2000, the value of shipments for the iron- and steel-forging industry remained relatively unchanged at approximately \$4.87 billion. Non-ferrous forgings also remained relatively constant for the 1997 to 2000 period at approximately \$1.84 billion. Figure 4-2 shows the four-year trend.

**FIGURE 4-2. VALUE OF SHIPMENTS FOR IRON AND STEEL AND NON-FERROUS FORGINGS (MILLIONS OF 1997 DOLLARS)**

SOURCE: INTERNATIONAL TRADE ADMINISTRATION, INDUSTRY SECTOR DATA.

**TABLE 4-1. NORTH AMERICAN FORGING TONNAGE FOR INDUSTRY MEASURES FOR 2001 (TONS)**

Forging Type	Ferrous	Non-Ferrous
Closed-Die Forging	1,682,427	50,273
Open-Die Forging	372,317	8,931

SOURCE: FORGING INDUSTRY ASSOCIATION.

Ferrous, closed-die forgings represent the largest type of forgings produced in North America, as shown in Table 4-1.

### EMPLOYMENT

Between 1997 and 2000, employment increased by almost 7 percent for non-ferrous-forging industries and by less than 1 percent for iron- and steel-forging industries. However, iron- and steel-forging industries accounted for almost three times the number of employees as non-ferrous-forging industries (25,375 versus 10,417 employees, respectively [ASM, 2001]). Table 4-2 shows industry employment from 1997-2000.

### CAPITAL EXPENDITURES

Between 1997 and 2000, capital expenditures for iron and steel forging, as well as non-ferrous forging, decreased by approximately 27 percent. In 2000, capital expenditures for iron- and steel-forging industries, as well as non-ferrous forging industries, totaled \$167 million and \$99.1 million, respectively.

### U.S. GLOBAL POSITION

The U.S. forging market has a value of over \$6 billion; however, U.S. imports of forgings total \$1.7 billion annually. Domestic forgers have lost market share, both home and abroad, to overseas companies that can

**TABLE 4-2. U.S. FORGING INDUSTRY ECONOMIC INDICATORS**

	Iron and Steel Forging				Non Ferrous Forging			
	1997	1998	1999	2000	1997	1998	1999	2000
Value of Shipments (\$ million)	4,870	4,578	4,744	4,928	1,838	1,845	1,987	1,932
Value of Shipments (1997 \$ million)	4,870	5,378	4,690	4,872	1,838	1,786	1,895	1,849
Total Employment (thousands)	26.2	28.4	25.9	26.4	9.0	9.3	9.6	9.6
Production Workers (thousands)	19.8	21.2	19.4	19.6	6.9	7.0	7.2	7.3

SOURCE: INTERNATIONAL TRADE ADMINISTRATION, INDUSTRY SECTOR DATA. AVAILABLE ONLINE AT [WWW.ITA.DOC.GOV](http://WWW.ITA.DOC.GOV).

produce and sell lower-cost parts. In an international survey conducted by the Forging Industry Association, the surveyed offshore companies identified North America and Europe as the leading markets for forgings. Approximately 68 percent of the international companies surveyed indicated that they have been actively selling in North America since 1990. Major sources of U.S. forging imports are shown in Table 4-3.

Forgings are found in over 20 percent of the products comprising the gross domestic product of the United States. Forged components are used in applications that require high levels of strength, quality, and reliability at low manufacturing costs (see Table 4-4 for examples).

### 4.3 PROCESS DESCRIPTION

There are several processes used to make forgings for different applications and industry requirements. The three primary categories are:

**Cold Forging** — Cold forging involves either impression-die forging or closed-die forging at or near room temperature, requiring no heating of the forming stock or dies. Common cold-forging processes are coining/sizing, heading/upsetting, and extrusion. Cold forging is characterized by high production rates and good die life. The most common cold-forged metals are carbon and standard alloy steels.

**Warm Forging** — Common operating temperatures range from 800°F to 1,800°F. Warm forging has potential advantages over cold forging, such as reduced tooling loads, reduced press loads, increased steel ductility, elimination of the need to anneal prior to forging, and favorable as-forged properties that can eliminate heat treatment.

**Hot Forging** — To avoid strain hardening, hot forging is carried out at temperatures and strain rates high enough that recrystallization of the metal occurs simultaneously with deformation.

**TABLE 4-3. MAJOR SOURCES OF U.S. IMPORTS OF FORGINGS (1997)**

Country	Value (\$1,000)
Mexico	83,611
Canada	57,486
Italy	37,839
Germany	35,014
Japan	28,397
China	17,298
All Others	111,742
Total	371,387

SOURCE: AIM MARKET RESEARCH, OFFSHORE FORGINGS COMPETITIVE MARKET STUDY, MAY 2002.

TABLE 4-4. APPLICATIONS OF FORGINGS BY INDUSTRY

Industry	Applications
Automotive and Truck	<ul style="list-style-type: none"> <li>• Wheel spindles, kingpins, axle beams and shafts, torsion bars, ball studs, idler arms, pitman arms, and steering arms</li> <li>• In the powertrain: connecting rods, transmission shafts and gears, differential gears, drive shafts, clutch hubs, and universal joints</li> </ul>
Agricultural Machinery and Equipment	<ul style="list-style-type: none"> <li>• Engine and transmission components, gears, shafts, levers and spindles, tie-rod ends, spike harrow teeth, and cultivator shafts</li> </ul>
Valves, Fittings, Oil Field Applications	<ul style="list-style-type: none"> <li>• Flanges, valve bodies and stems, tees, elbow reducers, saddles, and other fittings</li> <li>• Oil field applications: rock-cutter bits, drilling hardware, and high-pressure valves and fittings</li> </ul>
Hand Tools and Hardware	<ul style="list-style-type: none"> <li>• Pliers, hammers, sledges, wrenches, and garden tools; as well as wire-rope clips, sockets, hooks, turnbuckles, and eye bolts; surgical and dental instruments; and special hardware for electrical transmission and distribution lines: pedestal caps, suspension clamps, sockets, and brackets</li> </ul>
Ordnance/Shipbuilding	<ul style="list-style-type: none"> <li>• Rifle triggers, nuclear submarine drive shafts, heavy tanks, missiles, armored personnel carriers, shells, and other heavy artillery</li> </ul>
Off-Highway Equipment/Railroad	<ul style="list-style-type: none"> <li>• Engine and transmission parts, gears, sprockets, levers, shafts, spindles, ball joints, wheel hubs, rollers, yokes, axle beams, bearing holders, and links</li> </ul>
General Industrial Equipment	<ul style="list-style-type: none"> <li>• Industries: steel, textile, paper, power generation and transmission, chemical, and refinery</li> <li>• Forged configurations: bars, blanks, blocks, connecting rods, cylinders, discs, elbows, rings, shafts, sleeves, and T's</li> </ul>
Aerospace	<ul style="list-style-type: none"> <li>• Commercial jets, helicopters, piston-engine planes, military aircraft, and spacecraft: bulkheads, wing roots and spars, hinges, engine mounts, brackets, beams, shafts, landing gear cylinders and struts, wheels, brake carriers and discs, and arresting hooks</li> <li>• Jet turbine engines: discs, blades, buckets, couplings, manifolds, rings, chambers, and shafts</li> </ul>

Some of the primary forging processes are:

**Open-Die Forging** — Sometimes called hand forging, open-die forging is performed by working the metal between flat or simply contoured dies with unrestricted metal flow using repetitive strokes and continuous manipulation of the handpiece. Most open-die forgings are rounds, squares, rectangles, hexagons, and octagons. Open-die forging is used to produce spindles, pinion gears, and rotors. All forgeable metals are suitable for open-die forging.

**Closed-Die Forging** — Also known as impression-die forging, closed-die forging is the shaping of hot metal entirely within the walls or cavities of two dies that come together to enclose the workpiece on all sides, exerting three-dimensional control. It is used for both low-volume and high-volume production. The process produces final or nearly final metal shapes and controls grain-flow direction. Complex asymmetrical shapes

that require a minimum number of operations for completion are suitable for closed-die forging. Metals appropriate for closed-die forging must possess two basic characteristics: low material strength and the ability to deform without failure equal to the amount of deformation required in the die.

**Hot-Upset Forging** — Hot-upset forging is used for enlarging and reshaping some of the cross-sectional areas of a bar, tube, or other uniform (usually round) sections. In this process, the heated forging stock is held between grooved dies, and pressure is applied to the end of the stock in the direction of its axis by a heading tool which spreads (upsets) the end by metal displacement. Hot-upset forging produces finished forgings ranging in complexity from simple headed bolts or flanked shafts to wrench sockets that require simultaneous upsetting and piercing. It is also used as a finishing operation following hammer (or press) forging, such as that used in making camshafts. Although most forgings produced by hot upsetting are of carbon or alloy steel, the process can be used for shaping any forgeable metal.

**Roll Forging** — Roll forging is the process of reducing the cross-sectional area of heated bars or billets by passing them between two driven rolls that rotate in opposite directions and have one or more matching grooves in each roll. Examples of roll forgings are airplane propeller-blade half sections, hand shovels and spades, tapered axle shafts, tapered leaf springs, table-knife blades, and agricultural and tradesman's tools. All forgeable metals are suitable for roll forging.

**Extrusion** — In this process, the workpiece is placed in a container and compressed until the pressure inside the metal reaches flowstress levels. The workpiece completely fills the container, where a ram forces it through an orifice to form the extruded product. Depending on the direction of motion between the ram and extruded product, extrusions can be classified as forward (direct) or backward (reverse). Extrusions can be solid or hollow. Tube extrusion is typical of forward extrusion, whereas backward extrusion is used more commonly for mass production of containers.

**High Energy-Rate Forging (HERF)** — High energy-rate forging is a hot or cold, closed-die forging process in which the stored energy of high-pressure gas is used to accelerate a ram to high velocities to deform the workpiece. The specific part, material, and design requirements determine the forging temperature. Refractory metals, low-carbon steels, and nickel alloys that have broad forging temperatures can be forged by HERF. Unsuitable metals include magnesium and beryllium alloy; high-carbon steels; high-strength aluminum alloys; and nickel-based, heat-resistant alloys.



**Ring Rolling** — Ring rolling is a hot forming process used to manufacture seamless rings that are accurately dimensioned and have circumferential grain flow. The workpiece is placed over a mandrel, and the roll gap between the mandrel and a larger diameter driven main roll is progressively reduced. Friction between the main roll and the ring causes the ring to rotate. As the radial cross section of the ring decreases, circumferential extrusion occurs in the direction of the ring rotation, and the ring diameter grows. The configuration can range from very flat washer-shaped rings to long-sleeve-type rings. Any forgeable metals can be ring-rolled. Typical materials include carbon and low-alloy steels, copper, brass, aluminum and titanium alloys, and high-strength nickel and cobalt-based alloys.

**Radial Forging** — Radial forging is performed with four hammers. A radial press puts the entire surface of the workpiece under compressive stresses by contracting the circumference of the workpiece equally. Common applications include bars with round, square, or rectangular cross sections starting from ingots or blooms; stepped solid shafts and axles for locomotives, railroad cars, and trucks; stepped hollow shafts for components in the automotive and aircraft industries; necks and bottoms of steel bottles; and couplings and joint tools.

**Rotary Forging** — This technique is considered to be a substitute for conventional drop-hammer or press forging. It is a two-die forging process that deforms only a small portion of the workpiece at a time. Tools moving radially in a continuous manner forge the workpiece until the desired shape is formed. Applications include flanges, hubs, cams, rings, tapered rollers, thin disks, and flat shapes. Any material that has adequate ductility and cold-forming qualities can be rotary forged.

#### 4.4 ENERGY AND MATERIALS CONSUMPTION

Compared to other technologies used to produce finished or semi-finished parts, metal-forming techniques, such as forging, consume relatively little energy. The total annual electricity consumption for the industry is approximately 1.67 billion kilowatt-hours. Most of the energy employed in metal forging is consumed during the heating process for warm and hot forging.

Energy costs for the hot forging industry are approximately six cents for every pound of steel forged. This energy cost represents 6 to 8 percent of the cost of a forging. Energy is consumed in direct heating of forge stock, press operation and equipment, and normalizing and cleansing of forgings. Additional indirect energy use occurs in facilities heating, air conditioning, and lighting.

Forging industry energy consumption is not well documented. Based on an

average specific heat of one to 3 Btu/lb/K for every pound of steel forged, approximately 2,000 to 4,000 Btu of energy is used to heat the stock. Assuming a similar range for aluminum, and using the year 2001 output values of Table 4-3, energy consumption for the forging industry ranges between 9 and 18 trillion Btu per year. When system inefficiencies and energy consumed in other areas of a forge shop are included, energy consumption can be as high as 6,000 to 8,000 Btu/lb of steel. This implies a high energy consumption estimate for the industry of 28 to 37 trillion Btu annually. Other energy consumption estimates for the industry are as high as 50 trillion Btu per year.

Common heating methods are gas-fired heating, resistance heating, and induction heating. The industry uses electricity for billet manufacture, billet heating, press operation, heat treatment, and final machining. Natural gas is used for billet heating, air conditioning, and heat treatment; however, electricity is the primary energy source for billet heating. Typical energy consumption for aluminum billet heating is 1,600 Btu per pound.

When compared with the gas-fired furnaces typically used in forges, induction heating provides advantages of lower operating costs, improved die life, use of less metal due to limited scale and instant on/off operation, and flexible furnace operation time (gas-fired furnaces must operate continuously).

Forging/forming represents one of the most common uses of induction power, with power levels of up to 10,000 kilowatts. In induction heating, a high-frequency electric current is passed through a coil surrounding the workpiece, inducing an electromagnetic field in the piece. The magnetic field then produces eddy currents in the workpiece, and the electrical resistance of the workpiece to the flow of current heats the piece. Power consumption in induction heating is dependant on the workpiece material, the required temperature, and the design of the induction coil. Typical operating efficiencies are 6.0 to 6.5 lb/kWh when heating steel from ambient to a temperature of 2,200°F in a helically wound coil, and 7.0 to 7.5 lb/kWh when heating brass from ambient to 1,400°F in a similar helical coil.

Efficiency is reduced in systems where heating continuously (one part after the other) is not practical or when different coil arrangements are used. For example, a channel, or “C” type, coil arrangement may only be 65 percent as efficient, resulting in a rate of approximately 4.0 lb/kWh. Table 4-5 shows induction-heater efficiencies for different metals at different temperatures, as reported by Korean induction heater manufacturer Dongseo Mechatronics Company, Limited.

In the last ten years, energy purchases for heat and power have increased at an average rate of five percent. In 2001, energy purchases expressed as a

**TABLE 4-5. INDUCTION-HEATING EFFICIENCIES**

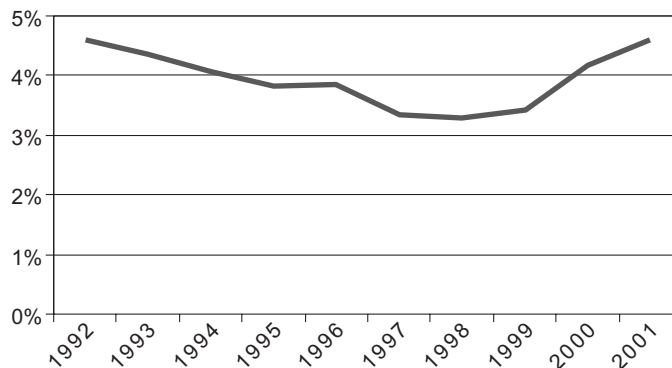
Material	Final Temp. [°F]	Efficiency
Carbon Steel	2,300	0.625
Carbon Steel	1,300	0.75
Stainless Steel	2,300	0.55
Brass	1,500	0.45
Copper	1,650	0.35
Aluminum	900	0.35

SOURCE: DONGSEO MECHATRONICS Co., LIMITED.

percentage of shipments totaled 4.6 percent, the highest level in the last 10 years. Figure 4-3 shows a ten-year trend of energy purchases for heat and power as a percentage of shipments.

#### 4.5 ENVIRONMENT

All production steps—pre-treatment, forming, and post treatment—produce residual waste, materials, and emissions, (e.g., lubricants, cleaning agents, and

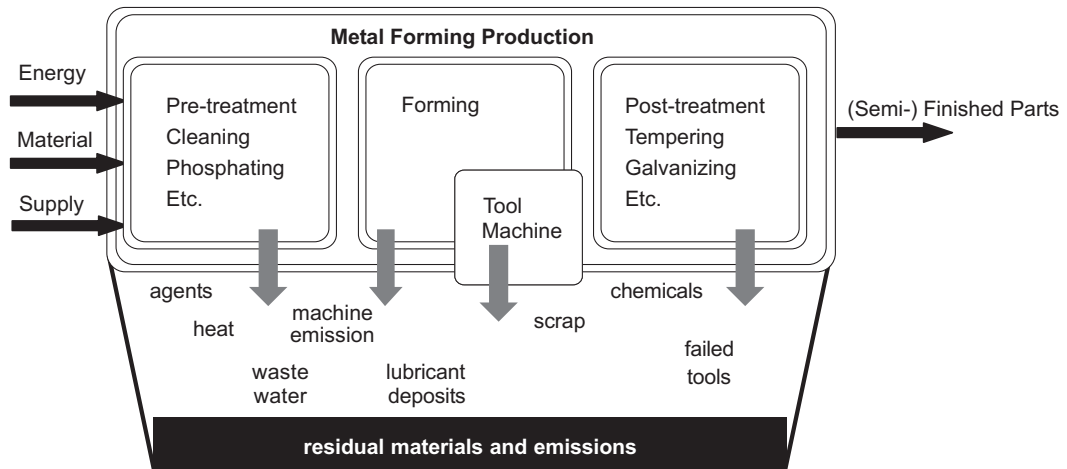
**FIGURE 4-3. ENERGY PURCHASES FOR HEAT AND POWER AS A PERCENTAGE OF SHIPMENTS, 1992-2001**

SOURCE: U.S. DEPARTMENT OF COMMERCE, ANNUAL SURVEY OF MANUFACTURES, STATISTICS FOR INDUSTRY GROUPS AND INDUSTRIES, 1993, 1994, 1996, 2001.

sludge) which all have to be handled. Figure 4-4 shows inputs and outputs during the pre-forming, forming, and post-treatment production steps.

##### 4.5.1 AIR EMISSIONS

Most air emissions from cleaning result from the evaporation of chemicals

**FIGURE 4-4. INPUT, OUTPUT, AND ENVIRONMENTAL IMPACTS IN FORMING PRODUCTION**

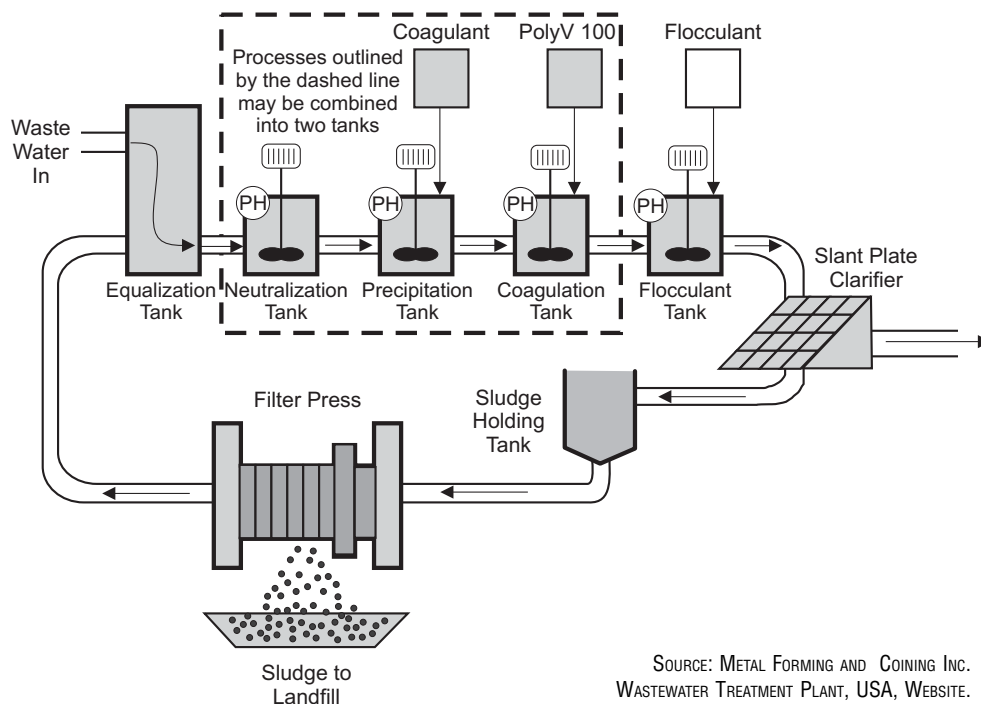
during solvent degreasing and emulsion-cleaning processes. These emissions can occur from volatilization of the solvents during storage, fugitive losses during use, and direct ventilation of fumes. In 1999, pollution abatement capital expenditures for the non-ferrous forging industry totaled \$2.4 million.

#### 4.5.2 EFFLUENTS

Wastewaters are generated during processes such as mechanical cleaning, degreasing, rinsing, and pickling. These surface-treatment operations are usually followed by phosphating and/or lubrication. The phosphating process involves applying a phosphate coating on the stock to condition the surface for cold-forming operations. Phosphatizing waste requires a complex treatment process because of secondary by-products such as acids, caustics, and soaps, as well as the phosphate compounds. Solid wastes (e.g., wastewater treatment sludges, still bottoms, cleaning tank residues, machining fluid residues, etc.) may also be generated by the cleaning operations. In 1999, pollution abatement capital expenditures for the forging industry totaled \$4 million, of which \$3.8 million were accounted for by the non-ferrous forging sector.

An innovative wastewater treatment process has been implemented at an Ohio-based metal forming and coining plant. In this process (Figure 4-5), waters from post-forming cleansing are sent to a large equalization tank. Zinc phosphates are segregated into a waste dump tank rather than hauled to a landfill. The top portion of the liquid is recovered, and water is removed from the lower settled solids in a filter press. Separate holding tanks are used

FIGURE 4-5. WASTEWATER TREATMENT PROCESS



SOURCE: METAL FORMING AND COINING INC.  
WASTEWATER TREATMENT PLANT, USA, WEBSITE.

for the acid, iron phosphate, and alkaline dumps, which are later transferred to an equalization tank. The combined wastewaters are then sent to a precipitation tank, a pH-controlled neutralization tank, a slant-plate clarifier, a sludge thickener tank, and a filter press. Clear-treated water from the top of the clarifier is discarded into a sewer, while the settled sludge from the bottom of the clarifier is pumped to a sludge thickener tank and then to a filter press. Filtrate from the filter press is sent back to the equalization tank, and the sludge is sent to a landfill. The recovered zinc phosphate liquid is reused in the zinc phosphate tank.

Cutting oils (such as ethylene glycol), degreasing and cleaning solvents, acids, alkalis, and heavy metals are usually used for metal-fabrication processes. The oils are employed in forming and metal cutting. Solvents such as trichloroethane and methyl ethyl ketone, alkalines, and hydrochloric and sulfuric acids are used to clean metal surfaces. Aqueous non-VOCs are popularly used to clean the metals whenever possible. The use of 1,1,1-trichloroethane and methyl ethyl ketone is declining. High amounts of waste are produced through the use of these lubricants and solvents, resulting in high disposal costs and an unpleasant working environment.

Table 4-6 summarizes the material inputs, air emission sources, wastewater contents, and solid wastes generated during metal cutting and forming processes. Scrap materials represent approximately 15 percent of the total production in the U.S. forging industry. At the current production rate, this translates to \$900 million per year of lost production. The high rate of scrap materials is partly due to an inability to inspect forgings while they are hot. This time delay allows imperfections to remain undetected until other forgings with the same imperfections have been made, resulting in energy, time, and economic losses.

**TABLE 4-6. INPUTS AND OUTPUTS FOR METAL CUTTING AND FORMING**

<b>Material Input</b>	<b>Air Emissions</b>	<b>Effluents</b>	<b>Solid Waste</b>
Cutting oils, degreasing and cleaning solvents	Solvent wastes (e.g., 1,1,1 - trichlorethane, acetone, xylene, toluene, et cetera)	Waste oils (e.g., ethylene glycol) and acid (e.g., hydrochloric, sulfuric, nitric), alkaline, and solvent wastes	Metal chips (e.g., scrap steel and aluminum), metal-bearing cutting fluid sludges, and solvent still-bottom wastes

As a consequence of the high temperatures required for forging and heat-treating operations, forgings produced from most metals acquire a thin coating of hard, abrasive oxide known as scale. Scale is formed as a result of a chemical reaction between free oxygen in the furnace and the heated metal. Three common techniques exist that are suitable for removing scale before forgings can be used or further processed:

**Blast Cleaning** — Blast cleaning consists of high-velocity bombardment of steel or iron shot, hardened wire clips, aluminum oxide grit, or sand.

**Tumbling** — Tumbling is one of the oldest and simplest cleaning methods. Forgings are placed in a barrel apparatus, together with abrasives and small bits of metal, and the barrel is rotated. The resulting abrasive action removes the scale.

**Pickling** — Pickling is the process of cleaning forgings by dipping them into a heated acid bath where scale is removed by chemical action. Forgings are generally bathed in an alkaline cleaning compound prior to pickling to remove oil or grease. Most carbon steel is pickled with sulfuric or hydrochloric acid, while stainless steel is pickled with hydrochloric, nitric, and hydrofluoric acids. After pickling, forgings are rinsed in clean, hot water to remove all traces of acid.

When the pickling baths lose their acidic strength, the depleted acids are replaced and neutralized with caustic soda. The waste acids are transported in tank trucks to regeneration facilities or disposal sites. Offsite waste treatment and disposal of waste pickling baths results in high costs which could be avoided with in-house acid recycling. Table 4-7 shows the estimated life-cycle energy requirements per ton of sulfuric acid.

**TABLE 4-7. ESTIMATED LIFE-CYCLE ENERGY REQUIREMENTS PER TON OF SULFURIC ACID (MILLION BTU)**

Activity	Energy Use
Mining and manufacture	0.8
Delivery to plant (300 miles)	0.8
Waste return shipping	4
Lime utilization	5
Total	10.6

SOURCE: D.R. OLSEN, 1997. PILOT TEST OF PICKLING PROCESS TO DETERMINE ENERGY AND ENVIRONMENTAL BENEFITS AND ECONOMIC FEASIBILITY.

#### 4.6 TARGETS OF OPPORTUNITY FOR IMPROVED ENERGY AND RESOURCE EFFICIENCY

A large opportunity exists for energy savings by replacing fossil-fuel heating with induction heating. This type of electric system, when compared to fuel combustion, also offers the environmental benefit of reduced emissions. However, induction heating is not suitable for large forgings (25 tons or higher).

The *Forging Industry Vision of the Future*, published in 1996, outlines a consensus of how the forging industry anticipated it would evolve by the year 2020. The document also identifies the specific goals that have the most direct impact on the competitiveness of the industry, and the required strategy to achieve these goals. Table 4-8 summarizes the strategic goals of the forging industry as stated in the *Forging Industry Vision of the Future*.

The *Forging Industry Vision* established the basis for the development of the *Forging Industry Technology Roadmap*, which was developed in 1997. The roadmap provides a blueprint of the required research and technology milestones via a tactical plan that ties the strategic targets in the industry

**TABLE 4-8. STRATEGIC TARGETS FROM THE FORGING VISION OF THE FUTURE**

<b>Tooling</b>	<b>Productivity</b>
<ul style="list-style-type: none"><li>• Increase die life by at least 10 times that of the current level</li><li>• Reduce per-part die system costs by at least 50%</li><li>• Produce tooling within 24 hours from time of order</li></ul>	<ul style="list-style-type: none"><li>• Improve per-employee productivity by 50%</li><li>• Reduce per-piece labor costs by 60%</li><li>• Achieve average forging facility up-times of 90%</li></ul>
<b>Energy</b>	<b>Quality</b>
<ul style="list-style-type: none"><li>• Reduce the forging process energy input by 20%, while cutting the per-piece energy cost by 75%</li></ul>	<ul style="list-style-type: none"><li>• Reduce rejected or returned work to less than 25 parts per million</li><li>• Achieve <math>\pm 8</math> sigma process control</li></ul>
<b>Material Utilization</b>	<b>Environment</b>
<ul style="list-style-type: none"><li>• Achieve a minimal overall reduction in raw material consumption of 15%</li><li>• Reduce the scrap rate (increase material utilization by 90%)</li></ul>	<ul style="list-style-type: none"><li>• Generate no harmful gas combustion products</li><li>• Eliminate aerosol emissions within forging plants</li><li>• Recycle all fluids necessary to forging operations</li></ul>

vision to the R&D portfolio. Both documents respond to the challenges that arise from increased global competition, technological changes, varying economic and market conditions, and increased customer demands with the overall goal of maintaining the U.S. leadership in high-quality, cost-effective forging components.

# 5. HEAT TREATING

## 5.1 INDUSTRY OVERVIEW

Heat treating is the process of heating and cooling a material in such a way as to develop specific structure, chemical composition, and physical properties.

Heat treating is used to:

- Soften metal, thereby facilitating shaping
- Harden parts, thereby increasing strength
- Put a hard surface on relatively soft components, thereby increasing abrasion resistance
- Create a corrosion-resistant skin
- Toughen brittle products

The heat treating industry is directly related to the metal producing and secondary processing industries. Classified by the government under NAICS 332811 (SIC code 3398), heat treating is a \$20 billion industry in the United States (\$75 billion worldwide). Materials that are heat-treated include semi-finished products used to make consumable or usable products. Materials processed include iron, steel, ferro-alloys, glass, and other nonferrous metals.

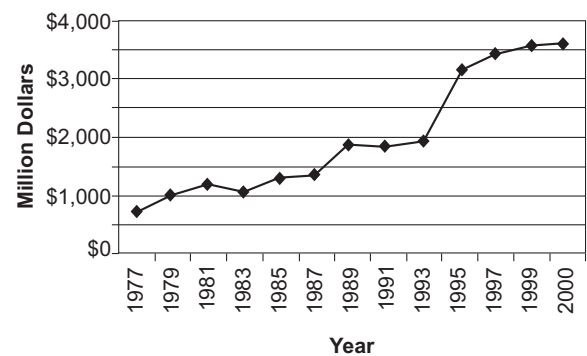
The total number of heat treating facilities in the United States is 5,000 to 6,000. Of these, 85 percent are captive (heat treating furnaces within a manufacturer's plant), while 15 percent operate as contract commercial operations. Commercial heat treating facilities are located throughout the United States but are concentrated in manufacturing regions such as the Midwest.

## 5.2 INDUSTRY PERFORMANCE AND MARKET TRENDS

The state of the heat treating industry is reflected in the health of its equipment suppliers. Domestic orders for industrial heating equipment were 26 percent lower for the first three quarters of 2002 compared to the same period in 2001. Domestic industrial furnace and oven orders experienced a sharper decline, down by 56 percent in the first three quarters of 2002. In 2001-2000, the value of shipments for the metal heat treating industry decreased by 17.6 percent in real terms, totaling \$3.16 billion (Figure 5-1).

The heat treating industry was adversely affected during the significant slowdown of the steel industry

**FIGURE 5-1. VALUE OF SHIPMENTS, 1977-2000 (MILLION 1998 DOLLARS)**



SOURCE: U.S. DEPARTMENT OF COMMERCE, ANNUAL SURVEY OF MANUFACTURES 2001.



during the mid-1980s. Subsequently, the industry implemented cost-cutting measures and made more effective use of resources to improve its overall efficiency. Over the past two decades the industry's emphasis on quality and innovation has improved its global competitiveness. However, the position of the U.S. heat treating industry in the global market is still affected by its conservative nature. "Standard" practices in Europe are considered "risky" in the United States. American industry is much less likely to install state-of-the-art technology; in fact, the biggest driver for furnace purchases is often the lowest capital costs.

In the 1990s, the domestic steel industry's import crisis, as well as the slow-down of the aircraft industry, adversely affected the industry's financial performance. In response, the industry has made even more adjustments (e.g., increased use of computerized systems) to reduce costs and improve efficiency. According to Integra Information, during the period 1995-2001 yearly industry revenues grew an average of 6.4 percent.

### 5.3 PROCESS DESCRIPTION

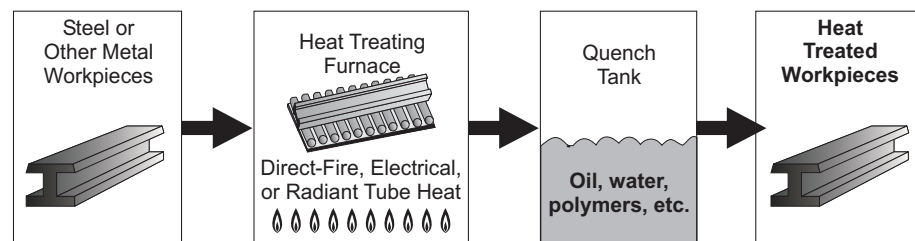
Heat treating requires three basic steps:

- Heating the workpiece to a specified temperature
- Holding the workpiece at that temperature for the appropriate amount of time
- Cooling the workpiece according to prescribed methods

Heating temperatures can be as high as 2,400°F and heating durations vary from a few seconds to several days. While some materials are cooled slowly in the furnace, others must be cooled quickly (quenched).

Water, brine, oils, polymer solutions, molten salts, molten metals, and gases are all used as quenching media. While each has characteristics that make it ideal for certain applications, 90 percent of materials are quenched in water, oil, gases, or polymers (Figure 5-2).

**FIGURE 5-2. HEAT TREATING PROCESS FLOW DIAGRAM**



The vast majority of heat-treated materials (80 percent) are iron and steel, including steel mill output such as bar and tube. Parts that have been cast, forged, welded, machined, rolled, stamped, drawn, or extruded are also commonly heat-treated.

Alloys of aluminum, copper, magnesium, nickel, and titanium may also be heat-treated. Aluminum alloy automotive castings are heat-treated to improve hardness and strength, while brass and bronze items are heat-treated to increase strength and prevent cracking. Additionally, titanium alloy structures are heat-treated to improve strength at high temperatures.

### HEAT TREATING PROCESSES

Many different types of heat treatment processes are used to obtain specific product results. Table 5-1 describes the most commonly used heat treating processes and their effects on the metal being treated, though many more

**TABLE 5-1. MAJOR HEAT TREATING PROCESSES**

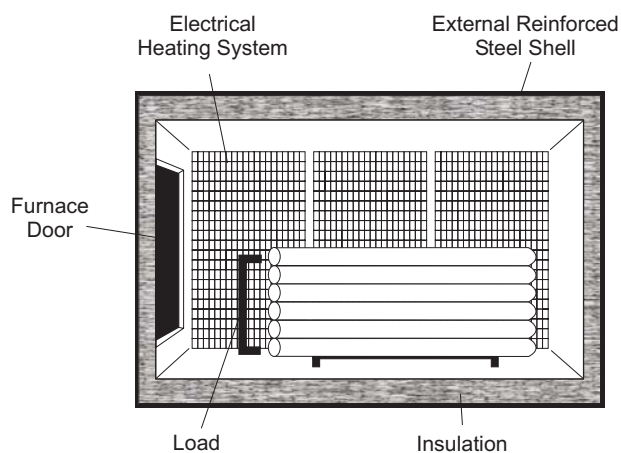
Process	Description	Effect on Metal	Applicable Metals
Annealing	Heat metal and hold it at a suitable temperature, then cool at a controlled rate	Softens material, improves machinability, facilitates cold work, improves mechanical or electrical properties, increases dimensional stability	Ferrous and non-ferrous alloys
Austenitizing	Heat metal to a temperature higher than the transformation range to form austenite	Forms an austenitic structure	Ferrous alloys
Carburizing	Heat metal in a carbonaceous atmosphere, then quench or cool to room temperature	Allows absorption and diffusion of carbon into solid alloys to harden surface layers	Ferrous alloys
Carbonitriding	Heat metal in a gaseous atmosphere of carbon and nitrogen, then cool to room temperature	Allows simultaneous absorption and diffusion of carbon into solid alloys to harden surface layers	Ferrous alloys (mostly low-carbon grades of steel)
Normalizing	Heat metal above its specific upper transformation temperature, then cool in still air	Conditions the metal by refining the grains of steel that have been subjected to high temperatures	Ferrous alloys
Nitriding	Heat metal in contact with a nitrogenous environment to a temperature below its lower transformation temperature	Introduces nitrogen into the surface layers of the metal which creates a hard, wear-resistant, and heat-resistant case	Ferrous alloys
Quenching	Cool metal rapidly by immersing in a liquid or gaseous medium	Cools metal	Steel, ferrous and non-ferrous alloys
Stress Relieving	Heat metal to an elevated temperature, then cool at a relatively slow rate	Relieves stresses that have been imparted from forming, rolling, machining, or welding	Steel, iron, and non-ferrous alloys
Tempering	Heat previously hardened or normalized metal to an elevated temperature below the transformation range	Relieves quenching stresses and ensures dimensional stability, thus increasing ductility and hardness	Steel

variations of heat treatment exist. The method chosen primarily depends on the metal composition and desired effect (e.g., softening, strengthening).

### FURNACE TYPES

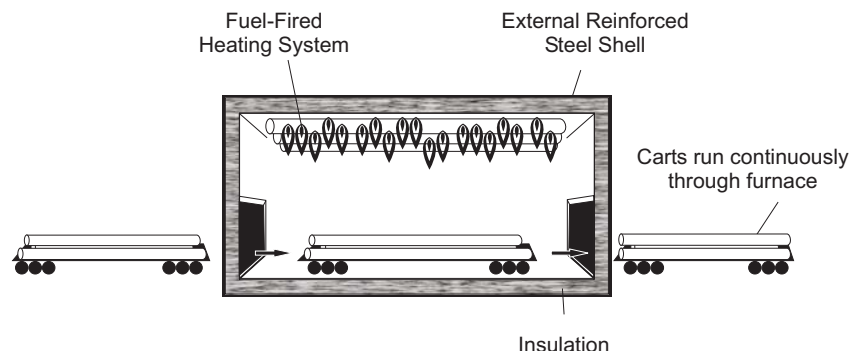
Furnaces can be categorized as either batch (e.g., box-type, car, elevator) or continuous (e.g., pusher, walking-beam, conveyor-type). Batch furnaces operate in cycles or batches, with the workpieces normally loaded and unloaded into the furnace chamber manually. Batch furnaces are normally used to heat low volumes of parts or to heat parts that require long cycle times. Figure 5-3 illustrates a typical electrically heated batch furnace.

**FIGURE 5-3. ELECTRICALLY HEATED BATCH FURNACE**



Continuous furnaces operate non-stop with a conveying system providing a constant load throughout the furnace. They are generally used for high-volume work. A typical direct-fired continuous furnace can be seen in Figure 5-4.

**FIGURE 5-4. DIRECT-FIRED CONTINUOUS FURNACE**



Some heat treating processes, such as carburizing, require a gas “atmosphere” in the furnace during the heating of the workpieces. The most common atmosphere is a mixture of 20 percent carbon monoxide, 40 percent hydrogen, and 40 percent nitrogen. This furnace atmosphere is typically generated

by partial combustion of natural gas and air in a heated catalytic chamber. The atmosphere is then maintained in the furnace so there is a reducing or non-oxidizing gas blanket surrounding the workpieces.

Salt baths are used instead of furnaces in some commercial heat treating operations, including liquid nitriding, austempering, and tempering. The work pieces are placed in molten salt baths that are heated externally (usually gas-fired) or internally (electrical/resistance heating). Sodium cyanide, barium chloride, potassium chloride, sodium carbonate, sodium chloride, and sodium cyanate are all types of molten salts used in salt baths. Each has characteristics that make it ideal for certain applications or processes.

### **FURNACE HEATING METHODS**

The majority of the energy consumed in heat treating is used to heat the furnace. Furnaces are usually heated by direct fire, electrical heat, or radiant-tube heat.

In a **direct-fired furnace**, the metal work pieces are directly exposed to the products of combustion. Direct-fired equipment is usually designed to use gas (propane, natural gas, or manufactured gas), oil (diesel fuel, No. 2 fuel oil, or other), or both as fuel. Fuel-fired furnaces usually provide lower energy costs, easy adjustment, and faster heat-up times. However, they can only be used with certain materials and require extensive ventilation systems and more manpower while creating a potential fire or explosion hazard.

**Electrically heated furnaces** are heated through the use of resistance heating elements. Although heating elements are usually nickel-chrome strips, other elements such as silicon carbide or molybdenum disilicide are sometimes used. Electrically heated furnace systems provide a more uniform heat pattern, do not generate pollutants at the furnace site (although the generation of electricity does create pollutants), and do not require extensive stacks and hoods. These systems are more expensive (capital and operating costs) and are less flexible than direct-fired systems.

**Radiant-tube heated furnaces** can be heated through either combustion or electrical heat. A radiant-tube furnace is usually used when the work chamber contains a controlled atmosphere or when the work pieces need to be protected from the combustion products. Electrically heated radiant tubes are also used to protect the heating element from the furnace atmosphere.

In recent years, the percentage of electrical furnaces has increased because:

- Vacuum processes are becoming increasingly common—electrical vacuum furnaces are well established, while gas vacuum furnace technology is still developing

- Electrically heated furnaces are preferred for high temperature applications ( $> 1,850^{\circ}\text{F}$ ) and more stringent uniformity specifications (tighter than  $\pm 10^{\circ}\text{F}$ )
- Gas-fired furnace designs require pressure in certain applications while electrical systems require no pressurization

### QUENCHING

A complete quenching system consists of:

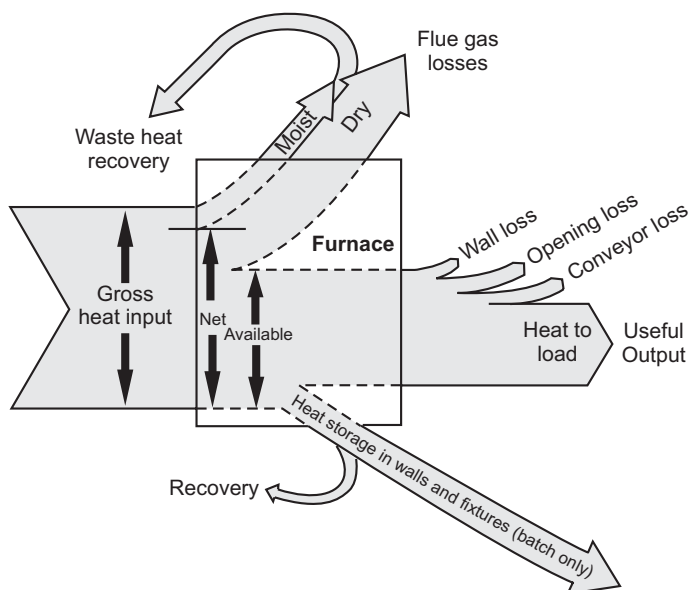
- A work tank
- Facilities for handling the quenched parts
- A quenching medium
- Equipment for agitation, cooling, heating, pumping, and straining/ filtering
- A quenchant supply tank

Quenching is a significant source of waste in the heat treating industry. Spent baths and wastewater generated when quenched workpieces are washed to remove either salt or oil that remains after the quenching process.

## 5.4 ENERGY AND MATERIALS CONSUMPTION

Heat treating facilities in the United States operate roughly 55,000 furnaces, 66 percent of which are gas-fired and 33 percent of which are electrically heated, with only minor amounts of oil consumed. These furnaces and associated equipment account for about 458 trillion Btu of annual energy use, with gas-fired furnaces consuming 337 trillion Btu (329 Bcf natural gas) and electrically heated furnaces the balance of 121 trillion Btu (Welling, 2002 and Gas Technology Institute, 1998).

FIGURE 5-5. HEAT LOSS IN A FUEL-FIRED FURNACE



Recent developments in electronics and computer technology have led to significant improvements in energy input (heating elements, burners, etc.) and control mechanisms. However, the operating costs for heat treating furnaces are closely tied to prices for natural gas and electricity.

Heating the furnace and load accounts for the most significant use of energy in the heat treating industry. In an electrically heated furnace, efficiencies range between 15 percent and 100 percent. Fuel-fired furnaces have efficiencies of 5 to 70 percent but are generally more economical because of the higher cost of electricity. As seen in Figure 5-5, fuel-

fired furnaces lose energy in many ways. Flue gas losses are most prevalent, and their recovery can significantly impact furnace efficiency. With all types of furnaces, heat loss becomes more severe as the furnace temperature is increased.

### COMMON WAYS TO IMPROVE ENERGY EFFICIENCY

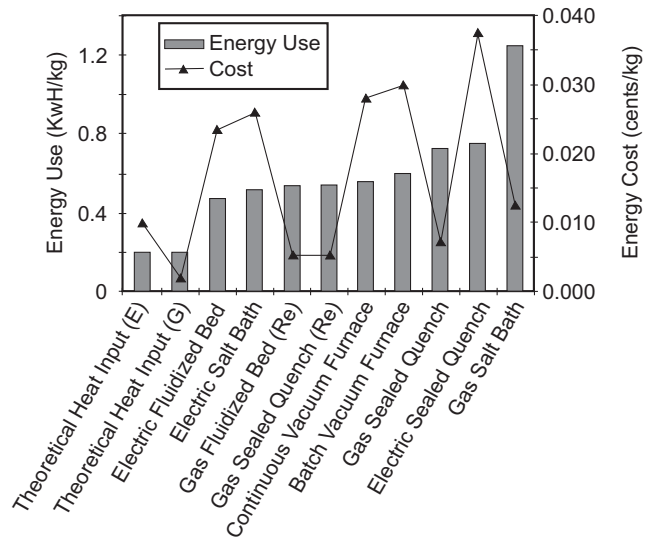
While energy use is typically lower in electric furnaces, use of these furnaces is more expensive because electricity is more costly than fossil fuels, as shown in Figure 5-6. As a result, direct-fired furnaces are more common, especially in areas where fuel oil or gas is readily available. Technologies and practices for improving energy efficiency of direct-fired furnaces are also more highly developed.

Improving the energy efficiency of gas- or oil-fueled heat treating furnaces can include combustion control, waste-heat recovery, and better furnace design. Proper control of the fuel-to-air ratio during combustion, achieved by metering the flow of gas and air into the burner or measuring the oxygen and carbon monoxide content in the flue gas, reduces flue gas losses. Pre-heating combustion air using high-velocity burners and pulse firing can also improve the heat transfer of a combustion system.

The recovery of waste heat involves the use of a recuperator or regenerator. Waste heat can be used in recuperators, which preheat combustion air by transferring heat from the hot flue gases to the inlet air (Figure 5-7).

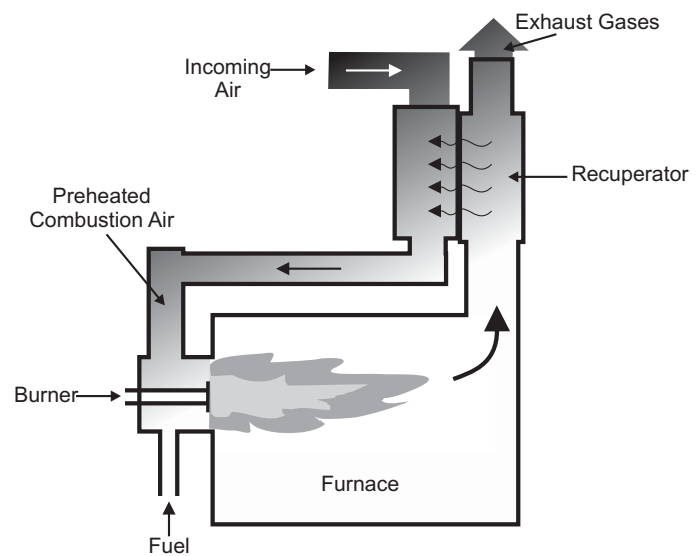
Regenerative burners are also used to preheat combustion air using cycles of different inlet/outlet flow patterns to transfer the heat from the flue gas to the inlet air (Figure 5-8). Regenerative burner systems usually operate at higher temperatures, providing greater fuel savings than recuperators. In addition to using the exhaust to heat the incoming combustion air, the waste heat can also be used to pre-heat the load itself by “passing” the gases over the work pieces (Thekdi, 2002).

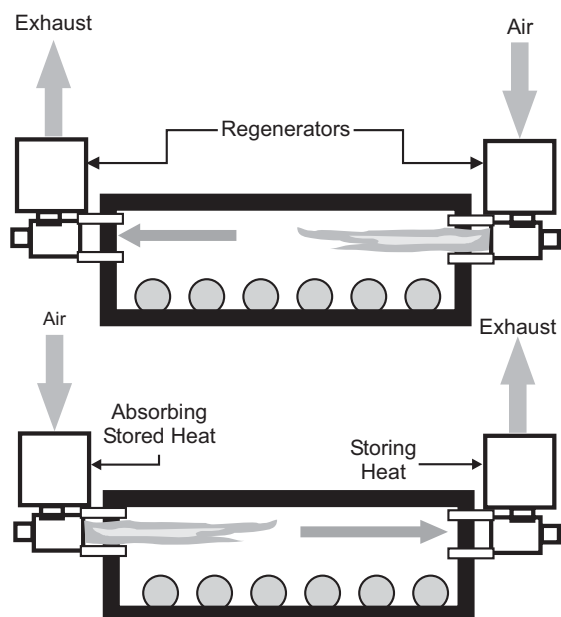
FIGURE 5-6. ENERGY USE AND ENERGY COST OF FURNACE OPERATION



\* Assumes soak temperature of 1,560°F, gas cost of 0.01 cent/KwH, and electricity cost of 0.05 cent/kg.

FIGURE 5-7. FURNACE RECUPERATOR



**FIGURE 5-8. FURNACE REGENERATOR**

Proper furnace design minimizes other heat losses than those in the flue gas. Using effective materials to reduce wall, conveyor, and opening losses, and all reduce furnace heat losses. Improving heat transfer from the flame to the load also increases efficiency. Process controls and furnace modeling and design tools can further optimize the furnace design for the heat treating application.

## 5.5 ENVIRONMENT

According to the U.S. Census Bureau, the U.S. heat treating industry used only \$1.0 million in capital expenditures for pollution abatement equipment in 1999 (DOC, 2002). However, this figure does not include expenditures by the 85 percent of heat treating facilities that are captive in other manufacturing industries. Table 5-2 lists the major environmental statistics for the heat treating industry.

**TABLE 5-2. KEY ENERGY AND ENVIRONMENTAL FACTS: HEAT TREATING**

Energy	Emissions	Effluents	Byproducts/ Hazardous Wastes
Ranges from 0.2 - 1.25 kWh/kg (0.62 - 3.87 10 <sup>6</sup> Btu/ton), depending on type of furnace/process	<p>Furnaces: Particulate emissions (smoke containing dust, soot, metallic particles), CO, NOx, and SOx</p> <p>Quenching Baths/Other: CO, CmHn, sub-micronic particles, including carbonaceous materials, HCl, HCN, and dust</p>	<p>Scrubbing water, cleaning water, and quenching media</p> <p>Constituents of concern: Oxides of Fe, Cr, and BaCl<sub>2</sub>; SO<sub>4</sub>; NO<sub>3</sub>; Cl; CN; and ash and asphalt residue</p>	Waste salts (cyanide)

### 5.5.1 AIR EMISSIONS

Two primary types of emissions from heat treating furnaces exist: those resulting from the combustion of fossil fuels (either on site or at the power plant generating the electricity used by the furnace) and process-related emissions from furnace atmospheres.

#### COMBUSTION EMISSIONS

Emissions in the heat treating industry are generated primarily through combustion of fuel oil or gas in direct-fired or fuel-fired radiant tube-heated furnaces, which result in NOx, CO, CO<sub>2</sub> and SOx air emissions. The control

of the fuel/air ratio is extremely important in minimizing the production of these pollutants, as well as in maintaining the efficiency of the furnace. Emissions from combustion of gas or use of electricity in heat treating furnaces are estimated in Table 5-3.

Electrically heated furnaces do not generate combustion emissions at the heat treating facility. However, emissions are created at the power plant or utility at which the electricity was generated. Those emissions are also estimated in Table 5-3.

**TABLE 5-3. ESTIMATED U.S. HEAT TREATING COMBUSTION EMISSIONS\***

<b>Pollutant</b>	<b>Gas/Oil Furnaces</b>	<b>Electrically Heated Furnaces</b>
NO <sub>x</sub> (metric tons)	35,848	56,762
SO <sub>2</sub> (metric tons)	128	77,414
Carbon Units (metric tons carbon equivalent)	4.86	6.84
VOCs (metric tons)	995	970
PM-10 (metric tons)	59	1,530

*\* Emissions are calculated using GPRA emission generation factors*

The metals heating and melting market is one of the largest consumers of natural gas, using over 450 billion cubic feet annually. A significant portion of this load is regulated by environmental laws such as the Clean Air Act Amendments (CAAA) of 1990. The metals industry uses high-temperature furnaces for its processes, and these temperatures lead to significant formation of NO<sub>x</sub>. Some portions of the country, such as southern California, have started their own NO<sub>x</sub> emission-reduction programs ahead of federal enforcement of CAAA rules. Cost-effective burner technology is needed to reduce NO<sub>x</sub> levels without jeopardizing the productivity of metals processing furnaces or the quality of the materials they produce (Gas Technology Institute, 2002).

### **FURNACE ATMOSPHERE EMISSIONS**

Another major source of air emissions is furnace atmospheres. Furnace atmospheres are used in carbonitriding, nitriding, and, most commonly, carburizing processes. An estimated 4,500 U.S. facilities using 15,000 furnaces have carburizing operations. The typical carburizing atmosphere is a mixture of 20 percent carbon monoxide, 40 percent hydrogen, and 40 percent nitrogen. Currently, the common practice for domestic carburizing furnaces is to vent waste oven atmosphere gas through gas flares to ambient air. Following flaring, this waste carburizing gas contains NO<sub>x</sub> and approximately 10,000 to 20,000 ppm CO. CO discharge from a typical medium-sized carburizing facility is approximately 60 to 110 tons per year. In addition to the compliance issue associated with discharging waste carburizing gas, energy is wasted because all vented gas must be replaced (Rich, 1996).



### **OTHER AIR EMISSION SOURCES**

Other sources of air emissions from heat treating operations include:

- CO, CNHN, and smoke created by the evaporation of quenching and tempering oil.
- HCl, HCN, and other corrosive gases created by the evaporation of salt bath, washing, and alkaline liquid.
- SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> dust, created from sandblasting dust (Fan, 1994).

### **POLLUTION CONTROL SYSTEMS**

Typical pollution control systems include fume collection strategies, emission control equipment, and ancillary components. Hoods and exhaust pipes are used to collect the furnace and quench bath emissions. Afterwards, exhaust is cooled and then processed in an air emission control system. Control systems vary considerably depending on exhaust chemical composition, temperatures, and consistency. The “worst” case conditions must be determined to design an appropriate air emission control system.

Common components of control systems include low-energy scrubbers and electrostatic precipitators.

**Low-energy scrubbers** serve as evaporative coolers to reduce the exhaust temperature, removing large particles of carbonaceous materials and acting as fire guards.

**Electrostatic precipitators** place a static charge on particulate suspended matter in a gas stream, then collect the particulates on oppositely charge plates. These units can collect particulates in the micronic and sub-micronic range (Topmiller and Denison, 1996).

#### **5.5.2 EFFLUENTS**

Effluents from the heat treating process include spent liquid quenching media and process water used for cooling, cleaning, and wet scrubbing. Typical wet scrubber systems used for controlling particulate emissions from metallurgical operations (e.g., multi venturi systems) use 5 to 15 gallons of water per minute (Mikropul, 2003). Quenching media are discussed in Section 5.5.3.

#### **5.5.3 WASTES, RESIDUALS, AND BY-PRODUCTS**

Spent cyanide baths, spent quenchant, wastewater generated in parts cleaning operations, spent abrasive media, refractory material, and plating are major heat treating industry wastes. Air pollution controls also create dusts that must be handled properly.

A significant amount of waste is generated in heat treating operations where cyanide-containing baths are used. Cyanide salts on the part being processed contaminate the quenching bath, rendering the bath a hazardous waste when spent. Wastes are generally in the form of a residue or salt sludge. In normal bath maintenance routines, sludge collected at the bottom of the pot is removed on a daily basis. This sludge must be disposed of and treated as hazardous waste. As the bath media is depleted, bath pots corrode. To minimize corrosion of the pot at the air-salt interface, salts are completely changed every 3 to 4 months.

Another source of waste is the quenchant media washing operation. Spent quenching media, especially oil, contains oxides of Fe, Cr and  $\text{BaCl}_2$ ;  $\text{SO}_4$ ;  $\text{NO}_3$ ; Cl; and CN. Ash and asphalt residue may be contained in the quenchant as well. The quenching media is re-used if possible, but must be rejected at a specified rate. Oil is one of the most commonly used quenchants in the heat treating industry; the quantity of waste oil handled as a hazardous waste is therefore substantial. Process cleaning water has the same constituents and must be treated before being release.

Additional sources of hazardous waste in the heat treating industry are parts cleaning and masking operations. Solvent, aqueous, and abrasive cleaning wastes are also generated for disposal or treatment (EPA, 1992).

## **5.6 TARGETS OF OPPORTUNITY FOR IMPROVED ENERGY & RESOURCE EFFICIENCY**

A *Research & Development Plan* was created in 1999 by the heat treating community. This report outlines and prioritizes the most immediate, short-term research challenges needed to achieve the industry's vision and improve its resource efficiency. The R&D plan was updated in 2001 to address the business and technological changes that had occurred since the publication of the initial roadmap. The most significant energy-related research needs are shown in Table 5-4.

The ASM Heat Treating Society (HTS) continues to work to achieve this plan by holding ongoing meetings of the HTS R&D Committee, holding a workshop on Vision2020 at the National Center for Manufacturing Sciences annual conference, and working closely with the U.S. Department of Energy and Oak Ridge National Laboratory. Additionally, the Center for Heat Treating Excellence is conducting research in four areas of heat treating: modeling of distortion and its control in an alloy steel and a nickel-based precipitation hardening alloy; quenching (control of the process); control of heat treatment for cast aluminum alloys; and computer modeling to predict optimum furnace loading and heat-up time. Other opportunities for improvement in heat treating processes include the optimization of furnace designs through computational fluid dynamics modeling, new equipment for better waste heat recovery, and real-time controls.

## Supporting Industries Energy and Environmental Profile

**TABLE 5-4. ENERGY AND ENVIRONMENTAL RESEARCH NEEDS FROM THE 1999 R&D PLAN FOR THE HEAT TREATING INDUSTRY****Develop Integrated Process Models**

- Quenching models/property databases to enable predictive quenching
- Electromagnetic models 3-D analysis and quantitative materials databases

**Real-time Process Sensors**

- Sensors that can control a system with multiple chemical and physical inputs
- Controlling algorithms to quantitatively integrate sensor inputs
- Real-time case-carbon sensors and quenching sensors to quantify heat transfer

**New Materials**

- Materials suitable for rapid heating technologies

**Energy Reduction**

- Energy map of heat treating facilities
- High heat-transfer heating and cooling systems
- Low-cost heat recovery and low-temperature heat utilization
- Identification of process changes to reduce heat treating energy requirements
- Hybrid natural gas/electric heating systems to minimize process energy cost

**Environmental Impact**

- Pollution-prevention strategies and/or pollution-control technologies
- Alternative quenchants to oil
- Alternatives to  $\text{NO}_3/\text{NO}_2$ , CN, and BA salts, and solvent cleaners
- Heat treating changes or pollution treatment technologies that eliminate air emissions

The future of U.S. heat treating will depend on the industry's ability to reduce energy consumption, process times, production costs, and emissions while improving product quality and uniformity. Technological advancements and process improvements will allow the U.S. heat treating industry to flourish in the 21<sup>st</sup> century.

# 6. POWDER METALLURGY

## 6.1 INDUSTRY OVERVIEW

Powder metallurgy (P/M) is a highly developed method of manufacturing ferrous and nonferrous components from metal powders. The P/M process is a cost-effective way to produce simple or complex components at, or very close to, final dimensions at production rates ranging from a few hundred to several thousand parts per hour. Because P/M technology is also applied to non-metallic materials and material combinations, the term “PM<sup>2</sup>” (powder metallurgy and particulate materials) has gained use throughout the industry, recognizing the important and growing role non-metallic materials play in many markets. However, for simplicity, the term P/M will be used in this chapter to denote both the process and the industry.

P/M applications fall into two main groups:

- Components difficult to make by any other production method, such as porous bearings; filters; components made from tungsten, molybdenum, or tungsten carbide; and many types of hard and soft magnetic components
- Components for which P/M is a cost-effective alternative to machined components, castings, and forgings, such as automotive clutch plates, connecting rods, cam shafts, and planetary gear carriers

P/M components are used in a variety of markets, most notably, metal cutting and automotive, as well as recreation and hand tools, household appliances, industrial motors and controls, hardware, and business machines. P/M components can also be found in electronics, aircraft turbine engines, riding lawn mowers, surgical instruments, oil/gas well drilling equipment, and tractors.

### 6.1.1 INDUSTRY STRUCTURE

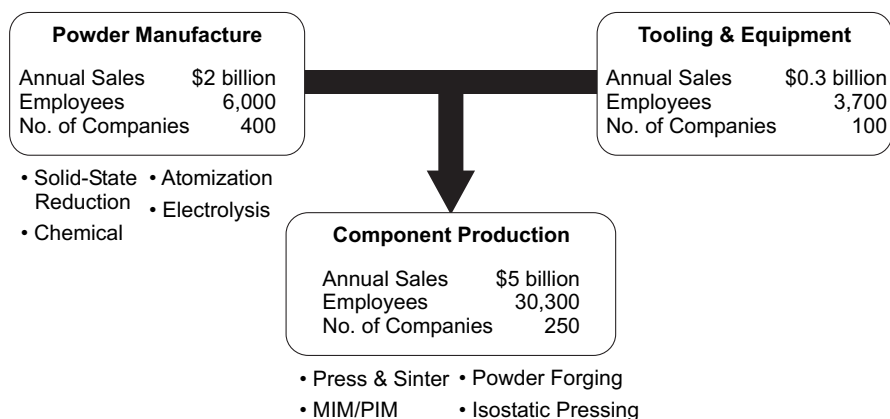
The P/M industry is often divided into three segments (see Figure 6-1):

**Powder Producers** — Worldwide metal powder production exceeds 1 million tons annually. In 2000, the value of U.S. metal powder shipments alone was near \$2 billion, though North American metal powder shipments declined in 2001 to 485,952 tons, a 14 percent decrease from 2000 shipments. The most common metal powders available are iron and steel, tin, nickel, copper, aluminum, and titanium, as well as refractory materials such as tungsten, molybdenum, and tantalum.

#### DEFINITIONS

**P/M** - powder metallurgy process used to create semi- and fully-dense components from metal powders.

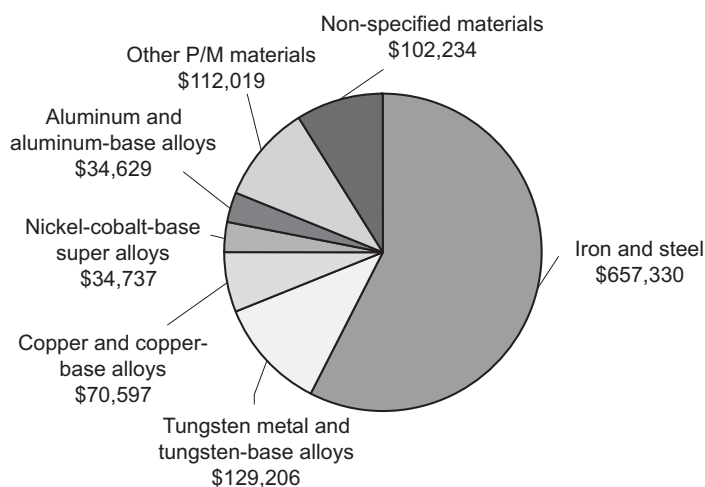
**PM<sup>2</sup>** - “powder metallurgy and particulate materials,” denoting the use of the P/M process with both metal and non-metallic particulate materials. PM<sup>2</sup> is also often used to refer to the industry that uses these materials to create near net-shaped and net-shaped components.

**FIGURE 6-1. STRUCTURE OF THE P/M INDUSTRY**

SOURCE: METAL POWDER INDUSTRIES FEDERATION.

**Tooling and Equipment Makers** — Approximately 100 tooling and equipment companies serve the P/M industry in the United States, accounting for \$300 million in sales annually. Companies in this sector supply equipment and technology for compaction and/or sintering processes, including presses, dies, and furnaces.

**Component and Product Producers** — North American P/M component producers account for approximately \$5 billion in sales annually – as large as the rest of the global industry combined. Component producers are often custom fabricators acting as job shops for OEMs. While only a few North American companies have their own captive or in-house suppliers of P/M components (e.g., Caterpillar, Black & Decker), P/M component producers serving as stand-alone processing companies are largely a North American trend.

**FIGURE 6-2. P/M COMPONENT PRODUCTION STATISTICS, 1997 (TOTAL VALUE OF SHIPMENTS: \$1,143,570)**

SOURCE: U.S. CENSUS DEPT., 1999.

The most recent U.S. government statistics for P/M component manufacturing is from the 1997 Economic Census, Manufacturing Industry Series. P/M component manufacturing is classified by the NAICS code 332117, although this classification only captures a fraction of the number of establishments in the industry as reported by MPIF, the main national trade association. (Figure 6-2 shows value of shipments data reported in the Economic Census.) Alternatively, SIC code 33991 represented “metal powders, paste, and flakes,” which included powder producers. In a 1996 EPRI report, it was estimated that powder producers constituted 70 percent of the total SIC code (EPRI, 2000).

Though other sources cite the number of P/M component manufacturing companies as 200 (Apelian, et. al., 1998, the range of data discrepancies makes generalizations about the industry difficult (see table 6-1 for comparison). In most cases, this document will rely on MPIF data for industry and market statistics, as it represents the broadest cross-section of the industry. The difference between the Census and MPIF statistics may be partially explained by recognizing that the Census data includes mainly press-and-sinter manufacturing operations, while MPIF data includes other industry operations such as metal injection molding, isostatic pressing, and powder forging. These processing options are all branches of the core P/M technology and are further described in Section 6.3.

**TABLE 6-1. COMPARISON OF U.S. CENSUS BUREAU AND MPIF ESTIMATES ON P/M COMPONENT MANUFACTURING**

<b>Metric</b>	<b>U.S. Census Bureau (1997) (U.S. industry)</b>	<b>MPIF (2000) (North American industry)</b>
Number of Companies	111	250
Value of Shipments	\$1.133 billion	\$5 billion
Employees	10,089	30,300

Ninety percent of P/M companies are classified as small businesses by U.S. government standards. However, approximately half of the industry's 40,000 employees work for a handful of large companies that dominate the industry, like Hoeganaes (Cinnaminson, NJ), the largest metal powder producer in the United States, boasting 25 percent of the iron and steel powder market and total annual sales of \$130 million (EPRI, 2000). By contrast, in the 1997 Economic Census, 102 of the 126 companies surveyed (81 percent) reported fewer than 100 employees. Those companies accounted for 46 percent of the total value of shipments for the sample size.

#### **THE VARIED P/M APPLICATIONS**

Automotive applications for P/M components also translate well into complementary markets, such as snowmobiles and lawn tractors.

Other applications include a wide range of consumer goods:

- Locking mechanisms
- Power tools
- Washing machines
- Firearms
- Wristwatches
- Photocopiers
- Postage machines
- Knives
- Fishing rods
- X-ray shielding
- Hydraulic mechanisms
- Canadian nickels
- Paints and coatings
- Drilling equipment for oil and gas wells

Some especially distinctive applications include:

- Iron powder: iron enriched cereals and bread (Americans consume more than two million pounds annually), hand warmers, waterproof cements, and as a carrier for toner in electrostatic copying machines
- Copper powder: anti-fouling paints for boat hulls, metallic pigmented inks for packaging and printing
- Aluminum powder: explosives, pyrotechnics, and solid fuels for rockets (such as boosters for the space shuttle program)

SOURCE: WHITE, 2002.

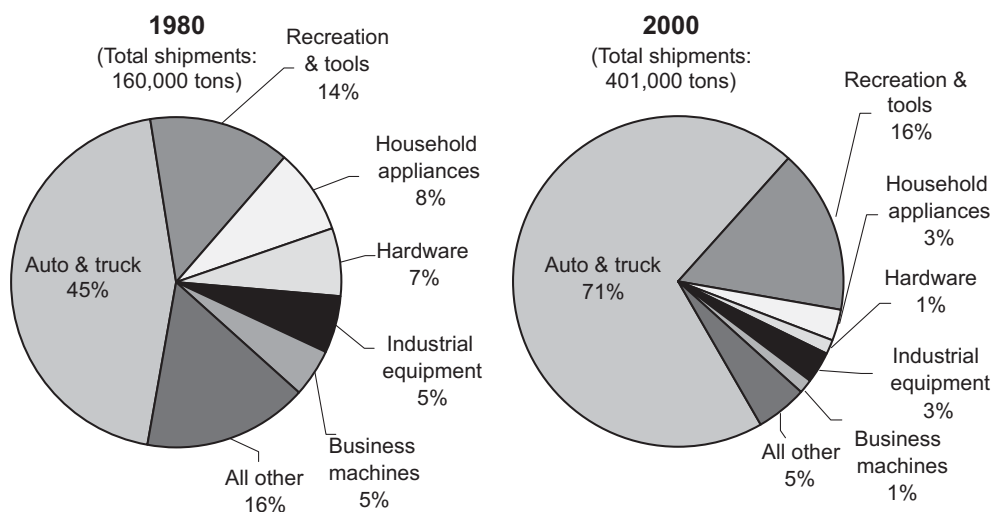
## 6.2 INDUSTRY PERFORMANCE AND MARKET TRENDS

Between 1990 and 2001, approximately 90 acquisitions occurred in the industry, 51 of those between 1997 and 2000 (White, 2001). This rash of consolidation led to the P/M industry increasingly consisting of large companies which in turn increased access to capital, thereby helping the industry increase manufacturing capacity, modernize equipment, and develop new materials.

### P/M MARKETS

As shown in Figure 6-3, the fortunes of the P/M industry are closely tied to those of the automotive industry, which consumes 70 percent of all ferrous P/M components produced. The amount of P/M components used in vehicles has more than doubled over the past 20 years, from an average of 16 pounds in 1978 to 37.5 pounds in 2001, with some larger SUVs containing more than 50 pounds. Key automotive applications include engines, transmis-

FIGURE 6-3. P/M FERROUS COMPONENTS MARKETS, 1980 AND 2000



SOURCE: METAL POWDER INDUSTRIES FEDERATION.

sions, and brake and steering mechanisms.

It is anticipated that P/M's growth in automotive markets will continue as new transmissions and engines utilize P/M parts to an even greater extent. Also, P/M design engineers are exploring additional automotive applications for aluminum powder (e.g., cam cap bearings, mirror brackets, shock absorber parts, pumps, and connecting rods) and stainless steel powder (e.g., flanges for exhaust systems and ABS sensor rings).

### MARKET TRENDS

From 1991 to 2000, the P/M industry enjoyed an era of sustained growth (Figure 6-4). Greater marketplace awareness of the technology coupled with

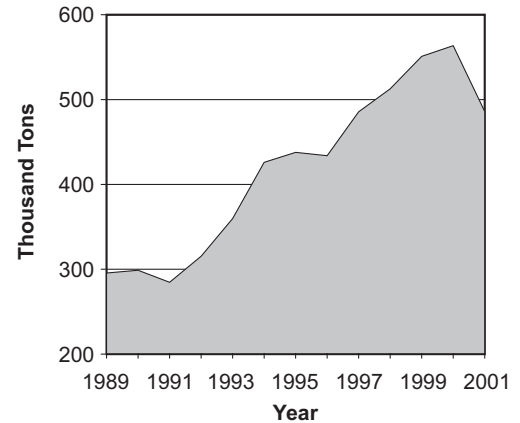
improvements in raw materials, processing techniques, and parts availability led to this substantial growth. Metal powder shipments peaked at 563,533 short tons in 2000, capping a decade that saw iron and steel powder shipments grow 210 percent, and the aluminum and copper powder shipments increase by 164 percent and 141 percent, respectively (White, 2001). Largely attributable to the softening of the economy and a 10 percent drop in U.S. light vehicle production, total powder shipments declined 14 percent in 2001, with some types of powder dropping even more drastically (e.g., nickel powder declined by 42 percent) (White, 2002). This decline precipitated the uncommon incidence of lay-offs throughout the P/M industry.

Other sectors of the P/M market that enjoyed growth during the 1990s included powder injection molding (PIM) and its subset metal injection molding (MIM), rapid prototyping, spray forming, metal matrix composites, metal foams, and nanoscale powders. At the close of the 1990s, the Metal Injection Molding Association estimated the size of the North American PIM market at \$245 million - \$125 million for metal parts and \$120 million for ceramic parts. In 2001, MIM component production dropped 16 percent, to approximately \$100 million, while ceramic injection molding fell 14 percent to approximately \$108 million. Though the current 10 percent estimated annual growth rate is a far cry from its former 20-25 percent peak, the 2003 outlook for MIM markets in automotive, medical, electronics, and telecommunications points to a solid and swift rebound. As shown in Figure 6-5, estimates on the global PIM market place it at \$706 million in 2000, with forecasted growth to \$2.0 to \$2.4 billion by 2010 (German, 2001). These estimates indicate a U.S. market share of 55 percent, with Asia and Europe splitting the remainder.

### GLOBAL POSITION

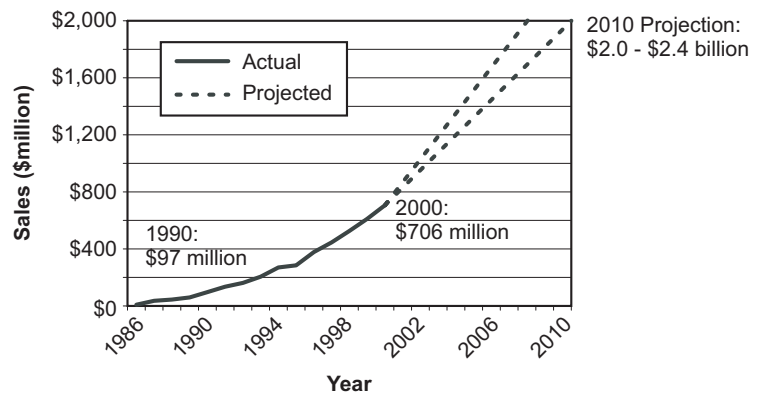
The last 40 years have seen U.S. powder producers account for about half of the global metal powder shipments and, for more than 50 years, the U.S. industry has also accounted for half of the world's P/M component production (Figure 6-6). This is partly due to the fact that U.S. producers are indepen-

**FIGURE 6-4. TOTAL NORTH AMERICAN METAL POWDER SHIPMENTS, 1989-2001**



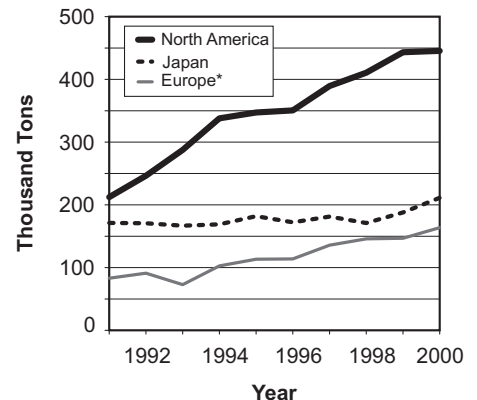
SOURCE: METAL POWDER INDUSTRIES FEDERATION.

**FIGURE 6-5. PIM WORLDWIDE SALES HISTORY**



SOURCE: GERMAN AND CORNWALL, 2001.

**FIGURE 6-6. INTERNATIONAL MARKET TRENDS COMPARISON, 1991-2000**



(Includes stainless steels after 1996)  
\* reflects P/M grade powders only

SOURCE: METAL POWDER INDUSTRIES FEDERATION.



dent companies able to pursue new applications and explore new opportunities at will, while European and Japanese counterparts typically remain part of larger firms, thereby lacking the ability to influence the growth and acceptance of new P/M applications (Apelian, et al., 2000).

Largely accounting for this domination of the marketplace is P/M's strength in the U.S. automotive sector; the average European and Japanese cars currently contain 16 pounds of P/M parts, 43 percent of the U.S. average of 37.5 pounds. In addition, lower energy and labor costs than in European and Japanese markets and supplier-initiated cost reduction programs have given the North American P/M industry a significant cost advantage over their international competitors. Apelian, et. al. estimate that in 1996 U.S. companies enjoyed a 20 to 30 percent cost advantage over Japanese parts producers. In response to this, European companies have begun to actively pursue potential acquisitions in North America, while the Japanese have responded with transplant attempts. These trends, along with the increased internationalization of automakers, has lead to the globalization of the P/M industry and may increasingly blend international markets in the future.

### **6.3 PROCESS OVERVIEW**

The P/M process begins by manufacturing powders using a variety of processing techniques. Then, the powders are mixed with lubricants and the mixture is molded in a die. Afterwards, the shapes are sintered—heated in a controlled-atmosphere furnace to bond the particles metallurgically with little or no melting. The component may then undergo a variety of additional manufacturing and finishing steps, such as coining, sizing, forging, rerolling, machining, heat treating, electroplating, and steam treating (Figure 6-7).

P/M typically uses over 97 percent of the raw material, and only minor, if any, machining is required. P/M parts may be sized for closer dimensional control and/or coined for higher density and strength. A range of processing options are used today, including press-and-sinter, MIM, hot isostatic pressing (HIP), and powder forging.

The basic P/M process is capable of producing simple or complex net- or near-net shaped components at production rates that range from a few hundred to several thousand components per hour. P/M gains acceptance among component manufacturers and users when value can be offered by reducing raw material needs and labor requirements through the elimination of extensive machining operations.

The P/M process possesses several inherent advantages, including:

- Raw material efficiency through recycling and elimination of secondary machining

- Industrial productivity through elimination of steps and increased automation
- Precision and special properties such as self-lubrication and controlled filtration

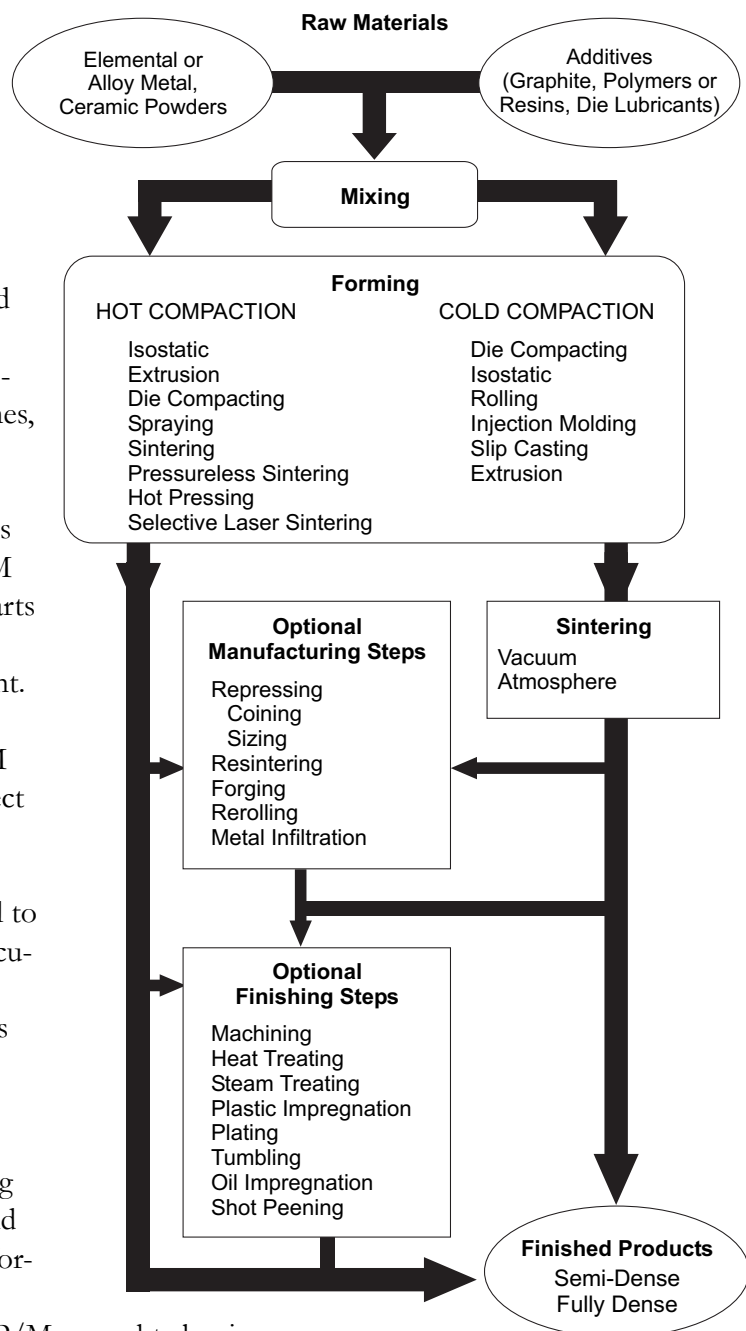
Increased scientific investigation of P/M technology by government, academic, and industrial R&D programs has improved strength properties and quality in automobile components, diesel and turbine engines, aircraft parts, and industrial cutting and forming tools. Such research has opened the door to increasingly complex contours and multiple levels, and though most P/M components weigh less than 5 pounds, parts weighing as much as 35 pounds can be fabricated in conventional P/M equipment. Ongoing refinement has also led to improvements in hot isostatic pressing, P/M forging, metal injection molding, and direct powder rolling.

Close dimensional tolerances are essential to the reliability and performance of a particular assembly. P/M's ability to control tolerances is one of the keys to its success in the conversion of many components from competing forming technologies.

On the leading edge of new manufacturing processes for improved product quality and productivity, P/M is a source of high performance and advanced particulate materials and alloys such as superalloys, tool steels, P/M wrought aluminum alloys, dispersion strengthened metals, thermal spray materials, metal matrix composites, intermetallics, and self-lubricating bearings.

There is essentially no limit to the variety of alloy systems that can be used to produce a shaped component with P/M. This gives designers flexibility in matching function and application requirements (e.g., strength, corrosion resistance, and other metallurgical and mechanical properties) with a material system that meets those needs.

FIGURE 6-7. THE POWDER METALLURGY PROCESS



SOURCE: METAL POWDER INDUSTRIES FEDERATION.

P/M's flexibility is becoming more pronounced with the advent of its use as a technique to manufacture components with novel material combinations. This trend is highlighted by the growing use of the term PM<sup>2</sup> at technical conferences, in the title of the industry's technology roadmap, and in other venues throughout the industry. Component designers can adjust the chemistry, density, and other P/M characteristics to provide a custom result uniquely suited for the intended application. Material options have expanded to include ceramics, nanophase materials, semi-metals, and functionally gradient materials.

### 6.3.1 POWDER MANUFACTURE

The first step in the overall P/M process is manufacturing the metal powders. Most powder is produced from scrap metals. P/M powders can be produced by taking elemental, partially alloyed or pre-alloyed metal powders and mixing them with lubricants such as graphite or waxes to produce a homogeneous mixture of ingredients. The density and consistency of the material during die compaction are critical to maintaining uniform part production. Additives can also be introduced to aid in machinability, wear resistance, or lubricity of the base alloy composition.

Four processes are primarily used in powder production: solid-state reduction, atomization, electrolysis, and chemical treatment.

**Solid-State Reduction** — Selected ore is crushed, mixed with a reducing species (e.g., carbon), and passed through a continuous furnace. In the furnace, a reaction takes place that leaves a cake of sponge metal which is then crushed, separated from all non-metallic material, and sieved to produce powder. Because no refining operation is involved, the purity of the powder is dependent on the purity of the raw materials. The irregular sponge-like particles are soft, compressible, and produces compacts of good green strength.

**Atomization** — Molten metal is separated into small droplets and frozen rapidly before the drops come into contact with each other or with a solid surface. Typically, a thin stream of molten metal is disintegrated by subjecting it to the impact of high-energy jets of gas or liquid. In principle, the technique is applicable to all metals that can be melted, and is used commercially for the production of iron, copper, alloy steels, brass, bronze; low melting-point metals such as aluminum, tin, lead, zinc, and cadmium; and, in selected instances, tungsten, titanium, rhenium, and other high melting-point materials.

**Electrolysis** — By choosing suitable conditions, such as electrolyte composition and concentration, temperature, and current density, many metals can be deposited in a spongy or powdery state. Further processing

— washing, drying, reducing, annealing, and crushing — is often required. Electrolysis is distinguished by offering high-purity and high-density powders, though it is not generally used due to high energy costs associated with the process. Commercially, use is mostly limited to high-value powders such as high-conductivity copper powders, but iron, chromium, and magnesium powders are also produced this way.

**Chemical Treatment** — The most common chemical powder treatments involve oxide reduction, precipitation from solutions, and thermal decomposition. Oxide-reduced powders are often characterized as “spongy” due to pores present within individual particles. Solution-precipitated powders provide narrow particle size distributions and high purity, while thermal decomposition is most often used to process carbonyls. These powders, once milled and annealed, can exceed 99.5 percent purity.

### **6.3.2 TOOLING AND EQUIPMENT DESIGN**

Tooling and equipment are designed to impart specific characteristics to a component based on a predetermined shape. Tooling allows precise control over the final product shape while attaining rapid production rates of thousands of components per hour. Because of the wide variety of P/M components produced, tooling and equipment are often customized for each desired component.

Most P/M dies are made of high-strength, durable alloys such as tungsten carbide or high-speed steel, which permits high volumes of consistent parts to be produced before wear of the tooling becomes a consideration. During compaction, a controlled amount of mixed powder is automatically gravity-fed into a precision die and compacted. Usually this is done at room temperature with compaction pressures ranging from 20,000 psi to 120,000 psi (typical compaction pressures range from 50,000 to 100,000 psi) depending on the density requirements of the part and powder being produced. The compacted “green” part has the size and shape of the finished part when ejected from the die and has sufficient green strength to be handled and transported to the sintering furnace.

### **6.3.3 COMPONENT PRODUCTION**

Component production, sintering, and finishing operations turn metal powders into final products. The four key processes in component production within the P/M industry are press and sinter, powder injection molding (PIM), isostatic pressing, and powder forging. The press and sinter process could be termed “conventional,” while the other processes are allied metalforming techniques that offer a broader range of design options, material choices, and other advantages.

**Press and Sinter** — The press and sinter process consists of four main stages: mixing the powders with a lubricant, pressing them together in a die under high pressure, heating the resulting green component at a temperature below the melting point of the main constituent (sintering), and any additional processing steps such as repressing or plating. Press and sinter is used to create conventional P/M components and products from iron, aluminum, and copper-based powders; specialty P/M products such as superalloys, porous products, friction materials, strip for electronic applications, high-strength permanent magnets, tungsten carbide cutting tools and wear components; and tool steels. Liquid-phase sintering, where parts are heated to a temperature above the lowest consistent melting point, is used to produce components from tungsten carbide, tool steels, and other hard metals. Generally, press and sinter produces semi-dense components.

During sintering, the green compact is placed on a mesh belt and slowly moved through a controlled atmosphere furnace, heated to a temperature below the melting point of the base metal, held at the sintering temperature, and then cooled. The sintering step transforms compacted mechanical bonds between the powder particles into metallurgical bonds by a solid-state transformation process.

**FIGURE 6-8. TYPICAL SINTERING TEMPERATURES**

Iron/Steel	2,000 - 2,400°F
Aluminum Alloys	1,100 - 1,150°F
Copper	1,400 - 1,800°F
Brass	1,550 - 1,750°F
Bronze	1,350 - 1,450°F
Hard Metals	2,200 - 2,900°F

SOURCE: EMPA WEB SITE.

Typical sintering furnaces are either natural gas fired or electrically heated with components passing through the furnace on a woven wire mesh belt. The trip through the furnace for a single part takes two to three hours, depending on the size of the part. As shown in Figure 6-8, typical sintering temperatures can range from 1,100°F to 2,900°. Variations on traditional sintering include high-temperature sintering, during which components are sintered at temperatures about 300°F higher than normal, and sinter

hardening—accomplished by using a controlled cooling rate in the cooling section of the belt furnace and transforming the steel matrix of a ferrous part to martensite, thereby eliminating the need for a secondary hardening step.

Controlled atmospheres are used during sintering to prevent oxidation and to promote the reduction of surface oxides that form on the component. Several atmospheres are used in industry, the most common being partially combusted hydrocarbons, cracked ammonia, dry hydrogen, and “synthetic” atmospheres. In practice, dry hydrogen is not frequently used due to its high relative cost.

The press and sinter processing option does have one main limitation — it is limited to two axes of design freedom. This limitation means compo-

nents with undercuts or multiple projections forming right angles with the pressing direction cannot be made directly.

**Powder Injection Molding** — Powder injection molding (PIM) and the subset metal injection molding (MIM) have emerged as competitive manufacturing processes for small precision components. PIM processes allow three axes of design freedom and are capable of producing complex shapes from many materials including metals, ceramics, intermetallic compounds, and composites, in both large and small volumes. New applications for components made from PIM and MIM are developing in the automotive, chemical, aerospace, business equipment, computer hardware, biomedical, and armaments industry sectors. PIM is used to produce components that may or may not be fully dense, depending on their intended application.

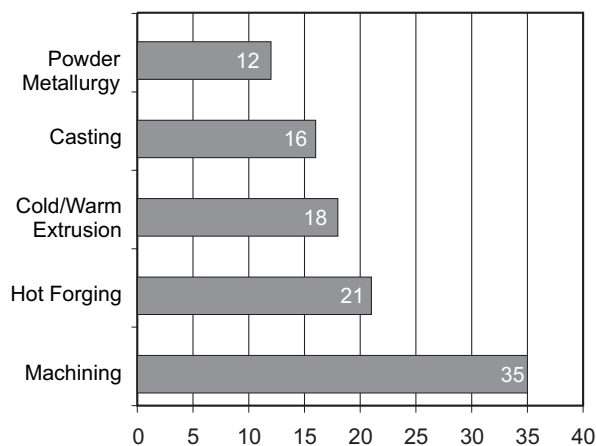
**Isostatic Pressing** — Isostatic pressing utilizes high pressures (around 65,000 psi) to uniformly compress a component to full density. This technique can be performed at high temperatures, called hot-isostatic pressing (HIP), or ambient temperatures, called cold-isostatic pressing (CIP). HIP eliminates the need for subsequent sintering, and both processes can produce fully dense components. Large, 3,000 pound compacts are possible using HIP, and the process can be used with unusual alloy combinations such as titanium-aluminides. CIP is gaining use in forming metal matrix composites for uses in aerospace, sporting goods, and electronic thermal management applications. For metal matrix composites, CIP is usually followed by hot extrusion or forging to full density.

The most significant difference between isostatic pressing and other methods of compaction is that isostatic pressing is performed in a pressurized fluid, such as oil, gas, or water. The powder mass is contained in a sealed container that provides a pressure differential between the powder and the pressurizing fluid. HIP is done in an inert gaseous atmosphere (usually argon or helium). Common pressures reach 15,000 psi, while temperatures achieve 2,300°F. CIP reaches pressures of 60,000 psi to form the component at high densities; it is then sintered in the usual fashion. HIP furnaces are typically heated with electrical elements made from a variety of materials according to required temperatures and pressures. Some CIP presses used for R&D purposes are capable of reaching 145,000 psi and operate at room temperature (MPR, February 2002).

**Powder Forging** — In this process, a powder blank is pressed to a shape halfway between a forging billet and the finished component. This compact, referred to as a preform, is pressed and hot forged to the finished size and shape in a closed die. The amount of deformation involved

is sufficient to give a final density close to that of solid metal. Consequently, the mechanical properties of powder forged components are comparable with wrought products.

**FIGURE 6-9. ENERGY REQUIREMENTS ( $10^3$  BTU/LB OF FINISHED PART)**



SOURCE: METAL POWDER INDUSTRIES FEDERATION.

## 6.4 ENERGY AND MATERIALS CONSUMPTION

Defining energy and material consumption requirements for P/M processes is complicated by the diverse range of materials and processing options available to both metal powder products and P/M component manufacturers. However, generally speaking, P/M is an energy- and material-efficient processing route for fabricating metal components. Figure 6-9 shows estimated energy requirements for metal forming processes; P/M has the lowest energy intensity of those analyzed by MPIF.

The most recent U.S. government statistics for the P/M industry come from the 1997 Economic Census, Manufacturing Industry Series, which presents data for the NAICS code 332117, P/M component manufacturing. The Census reports a total cost of fuels of \$9.231 million and total cost of electricity of \$20.811 million in 1997. The Census also reports a purchased electricity amount of 377.552 million kWh (4.0 trillion Btu using an electricity conversion factor of 10,500 Btu/kWh) in 1997. As discussed in Section 6.1.1, Industry Structure, this data likely represents a subset of the entire P/M component manufacturing sector of the industry.

Energy data for specific P/M processing routes are difficult to find. Some sources report the total electricity costs for producing MIM powders via atomization from steel materials at 1 to 2 percent of overall cost, depending on whether nitrogen or argon atomization is used (Diesch and Schulz, 1999). Table 6-2 shows the energy consumed during the production of iron powder via several processes and aluminum and copper powder via atomization.

**TABLE 6-2. ENERGY CONSUMPTION FOR THE PRODUCTION OF METAL POWDERS ( $10^6$  BTU/TON)**

Powder Type (Process)	Powder Production	Grinding, Drying, Cleaning	Heat Treatment	Total
Iron (Atomization)	8.4	1.7	5.0	15.1
Iron (Reduction)	13	1.9	5.0	19.9
Iron (Electrodeposition)	30	1.8	5.0	36.8
Iron (Direct Recycle)	—	1.6	5.0	6.6
Aluminum (Atomization)	22	1.7	—	23.7
Copper (Atomization)	11	1.7	3.5	16.2

SOURCE: EPRI INDUSTRY SEGMENT PROFILE, 2000.

Table 6-3 shows energy consumption estimates for the main P/M processing steps. Because of the wide range of materials and processing technologies used in the P/M industry, these energy consumption estimates do not apply to all specific cases. Rather, they are estimates made by the MPIF Roadmapping Oversight Committee for the industry as a whole and include a degree of aggregation. However, the key conclusion from this data—that powder manufacturing and sintering are by far the most energy-intensive steps in the P/M process—hold true for almost all P/M materials and processing routes that include sintering.

**TABLE 6-3. P/M PROCESS ENERGY ESTIMATES**

Process	Energy Requirements (10 <sup>6</sup> Btu/ton parts)
Powder Manufacture	19.0
Blending and Compaction	0.4
Sintering	17.3
Finishing	0.5
Miscellaneous	2.6
TOTAL	39.8

SOURCE: MPIF WHITE PAPER ON THE P/M INDUSTRY.

Applying these energy intensities to the 2000 production statistics of 401,000 tons yields a total estimated energy consumption of 16 trillion Btu. This estimate is not entirely accurate due to the variety of material and processing options, as discussed above, but it does provide an order-of-magnitude estimate of total energy consumption for the P/M industry.

#### THEORETICAL AND ACTUAL ENERGY REQUIREMENTS FOR P/M PROCESSES

In 1983, G.F. Bocchini published “Energy Requirements of Structural Components; Powder Metallurgy Versus Other Production Processes” in the journal *Powder Metallurgy*. In this paper, the author makes estimates regarding the theoretical minimum energy required in several P/M component production process steps, using iron powder and carefully specified process conditions. While process technology has changed significantly since 1983, Bocchini’s approach to estimating theoretical figures remains valid because it is based on thermodynamics and technological requirements (e.g., the theoretical minimum energy required to supply the work required for mixing) but not technological efficiencies (e.g., the efficiency at which equipment can perform mixing).

Table 6-4 shows the theoretical energy requirements as well as actual requirements and technological efficiencies as reported by Bocchini in 1983. The actual requirements have undoubtedly improved over the past 20 years, but because of the carefully specified cases in which Bocchini used to make estimates, comparisons to current industry-average energy requirements would not be meaningful.

The data clearly show that sintering is by far the most energy-intensive step in making P/M components, a conclusion that agrees with the process energy requirements shown in Table 6-3. Pre-sintering, which is required only for specific applications in which working stresses are high, is similarly energy-intensive.



**TABLE 6-4. THEORETICAL PROCESS ENERGY REQUIREMENTS FOR P/M COMPONENT MANUFACTURING AND COMPARISON WITH ACTUAL REQUIREMENTS, 1983<sup>1</sup>**

Process	Theoretical Requirements	Actual Requirements	Technological Efficiency
	(10 <sup>6</sup> Btu/ton processed)		
Mixing	0.001	0.002	0.59
Pressing	0.04	0.10	0.40
Sintering (Electric Furnace) not including losses	8.69	36.3	0.24
Sintering (Electric Furnace) including losses <sup>2</sup>		62.1	0.14
Sintering (Natural Gas Furnace)	13.57	90.5	0.15
Sizing	0.04	0.12	0.36
Pre-sintering (Electric Furnace) not including losses	5.13	17.1	0.30
Pre-sintering (Electric Furnace) including losses <sup>2</sup>		28.5	0.18
Pre-sintering (Natural Gas Furnace)	8.06	42.4	0.19
Re-processing	0.06	0.14	0.45

<sup>1</sup> For iron powder and carefully specified processing conditions; see reference for details.

<sup>2</sup> Using an efficiency of 40 percent in the electrical energy production process, as is used in the Bocchini paper.

SOURCE: BOCCHINI, 1983.

## 6.5 ENVIRONMENTAL OVERVIEW

The primary environmental concern in both the production of metal powders and P/M components is air emissions; particulate matter for powder producers, and volatile organic compounds (VOCs) for parts producers.

Metals, primarily from the melting of raw materials and the handling of finished powder for packing and distribution, constitute the majority of air emissions for powder producers. If gas atomization chambers are not properly sealed, fumes from the melting of raw materials or powder fabrication may also be released. Additionally, the discharge of collection systems, separation dewatering, drying, and handling of the final product can result in dusting.

VOCs are the primary air emission for parts producers. During sintering, the production of sintering atmospheres can lead to the release of nitrogen-, hydrogen-, and hydrocarbon-derived compounds. Additionally, delubing can result in the release of hydrocarbon vapors and metals, and cleaning the various parts and equipment used in parts production demands the use of solvents and cleaning agents which, through vaporization, can also contribute to air releases.

In addition to VOCs, particulate materials can be released at many points in the production process. For example, powders in motion inside the mixer and flowing to the die can result in air emissions.

For both powder and parts producers, transfers off-site consist almost exclusively of scrapped solid materials (metals) that do not meet design specifications.

The most recent and comprehensive examination of emissions and wastes generated by the P/M industry is *Environmental Trends for the U.S. Powder Metallurgy Industry* (Diaz-Triana and Isaacs, 2001), which focused on the characterization and impact analysis of chemical releases and transfer profiles for powder and part producers. The study specifically analyzed a sample of 72 facilities (12 powder and 60 part producers), most of which were members of the Metal Powder Institute Federation (MPIF). The study retrieved self-reported data on environmental information from the EPA Office of Environmental Information, Toxics Release Inventories on-site and off-site database (TRI Explorer), and the EPA Office of Environmental Information, Environmental Facts Database, (also known as the Envirofacts Warehouse).

## Air Emissions

For the powder and component production sectors combined, air emissions are the most significant release in terms of weight, accounting for 84.8 and 76.3 percent of total releases in 1993 and 1998, respectively. On-site releases in these years were almost exclusively air emissions, 99.1 and 98.3 percent for 1993 and 1998, respectively. Overall air releases decreased 24 percent during this time, from 1,205,308 pounds in 1993 to 918,518 pounds in 1998 (Table 6-5). These air emissions were dominated by VOCs which accounted for 84.5 percent of air emissions in 1998.

Metals make up the bulk of remaining air emissions, with copper, chromium, zinc, nickel, manganese and aluminum and their compounds the most significant overall. Shifts in individual chemical dominance have been observed; in 1993, copper constituted 52.4 percent of metallic air emissions, while in 1998 zinc composed the highest percentage, at 42.2 percent. Figure 6-10 shows the distribution of chemicals in air emissions from the facilities analyzed.

Off-site transfers are almost entirely metal, and are dwarfed in terms of weight by air emissions. However, between 1993 and 1998, metallic off-site transfers increased by 42

### OTHER EMISSIONS AND WASTE (BY PROCESS)

#### Powder Production:

- Equipment cleaning operations (solvents and emulsions)
- Vaporization during cleaning operations (VOCs)
- Scrap powder (contaminated, does not meet design criteria)

#### Parts Production:

##### Mixing:

- Admixed powders (dusting)
- Pre-alloyed powders (dusting)
- Diffusion alloyed powders (dusting)

##### Forming:

- Die compacting (powder overflow)

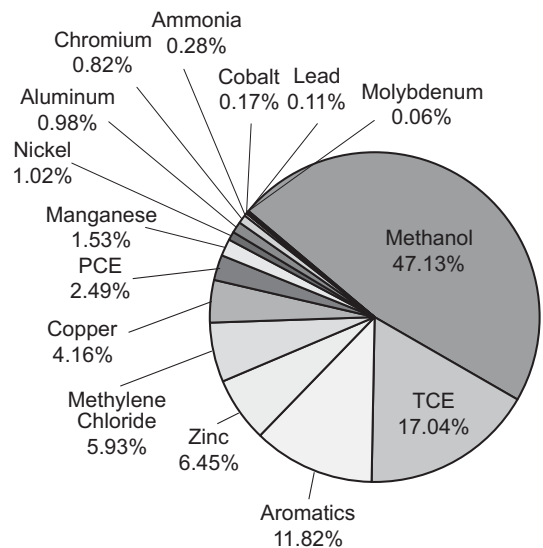
##### Optional Finishing Steps:

- Cutting, grinding processes (metals contaminated with cooling fluids)
- Machining (metal chips)

##### Other:

- Discarded parts due to quality control
- Spent cleaning solutions
- Cutting and grinding oils

FIGURE 6-10. DISTRIBUTION OF THE MAJORITY CHEMICALS IN TOTAL AIR EMISSIONS, 1998



SOURCE: DIAZ-TRIANA AND ISAACS, 2002.

**TABLE 6-5. TRI DATA FOR ON-SITE RELEASES AND OFF-SITE TRANSFERS FOR THE P/M INDUSTRY, 1993 AND 1998<sup>1</sup>**

	1993 (lbs)	1998 (lbs)	% change
<b>On-Site Releases: Air Emissions<sup>2</sup></b>			
Volatile Organic Compounds	936,524	776,607	- 17.1
Metals	250,704	136,859	- 45.4
Other	18,080	5,052	- 72.1
Total Air Emissions	1,205,308	918,518	- 23.8
<b>Off-Site Transfers<sup>3</sup></b>			
Metals	195,348	276,624	41.6
<b>Total Releases and Transfers</b>			
Volatile Organic Compounds	936,524	776,607	- 17.1
Metals	445,661	412,653	- 7.4
Other	38,695	13,903	- 64.1
<b>TOTAL</b>	<b>1,420,881</b>	<b>1,203,163</b>	<b>- 15.3</b>

<sup>1</sup> Based on analysis of TRI data submissions for 72 P/M facilities.

<sup>2</sup> Air emissions represented 99.1 and 98.3 percent of total on-site releases in 1993 and 1998, respectively.

<sup>3</sup> Metals accounted for over 99 percent of total off-site transfers for both 1993 and 1998.

SOURCE: DIAZ-TRIANA AND ISAACS, 2001.

percent, potentially indicating a growing trend for P/M companies to send solid wastes off-site for recovery or disposal.

### **POWDER, COMPONENT PRODUCERS EXHIBIT DIFFERENT RELEASE PROFILES**

Twelve powder producers and 60 component producers were included in the Diaz-Triana and Isaacs study. While both sectors reported 100 percent metallic off-site transfers, the air emissions profiles between powder and component producers varied significantly. In 1993, powder producers reported that almost 70 percent of their air emissions were metals, with VOCs accounting for the remainder; in 1998, the balance between metallic and VOC air emissions was nearly even. In stark contrast, component producers reported that over 90 percent of their air emissions were VOCs for both years.

**TABLE 6-6. TYPE OF AIR EMISSIONS FOR POWDER AND COMPONENT PRODUCERS (PERCENT OF TOTAL)**

<b>Powder Producers</b>	<b>1993</b>	<b>1998</b>
Metals	69.29%	50.45%
VOCs	30.7%	49.54%
<b>Parts Producers</b>		
Metals	4.52%	8.59%
VOCs	95.47%	91.40%

SOURCE: DIAZ-TRIANA AND ISAACS, 2001.

In terms of specific emission constituents, metallic air emissions in powder production primarily included copper, chromium, and zinc. Between 1993 and 1998, P/M companies reported a significant reduction in the quantity of copper (77 percent) and chromium (91 percent) released into the air, leading to a 66 percent overall reduction of air releases, while zinc, manganese, aluminum, cobalt, lead, and molybdenum air releases increased. VOCs were most represented by methylene chloride (MC), which increased

28 percent, and trichloroethylene, which increased 37 percent over the time frame considered.

For component producers, a total of nine VOCs are reported—four halogenated and five non-halogenated. The most relevant contributions to weight correspond to alcohols (mainly methanol), aromatics (benzene, toluene, and xylene), and TCE. There was a reduction in the amount of aromatics, ketones, and MC released into the air between 1993 and 1998, while TCE and alcohol air releases increased. VOCs in air releases decreased 16.6 percent in weight during the examined period.

## EFFLUENTS

During 1993 and 1998, surface water discharges, land releases, and underground water injection had a negligible contribution to Toxic Release Inventory data.

## OFF-SITE TRANSFERS

Off-site transfers accounted for 13.2 and 22.9 percent of total releases in 1993 and 1998, respectively, for P/M companies considered. Off-site transfers increased by 41.6 percent during that time, from 195,348 pounds in 1993 to 276,624 pounds in 1998. Metals accounted for 100 percent of transferred substances for both powder and part producers. Figure 6-11 indicates the distribution of chemicals in off-site transfers for 1998.

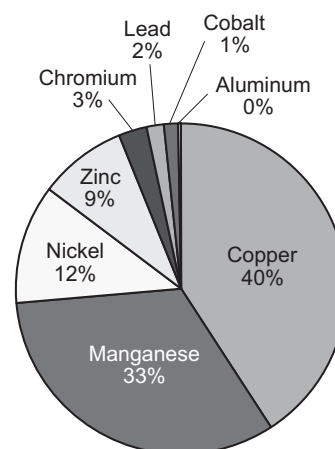
## TRI TRENDS

Diaz-Triana and Isaacs incorporated selected production data from the P/M industry with the TRI data to track environmental and economic performance with respect to industry growth by generating a pollution intensity index. Pollution intensity is an index, expressed as a ratio of releases or emissions per unit of manufacturing activity or production output.

Trends for releases in both P/M production sectors indicate opportunities for improvement in the management and operation of manufacturing processes:

- Higher metal content in air releases for powder producers resulted in higher toxicity indices, compared to the predominately organic releases by part producers
- Increased production output over the five-year period did not result in increased weight of emissions in all cases, suggesting some extent of control for air releases

**FIGURE 6-11. DISTRIBUTION OF CHEMICALS IN ALL OFF-SITE TRANSFERS, 1998**



SOURCE: DIAZ-TRIANA AND ISAACS, 2002.

- Transfers off-site show smaller reductions of releases per unit of production, indicating a potential opportunity to improve the P/M process by reducing the generation of solid wastes
- Ammonia and inorganic compounds, such as hydrochloric acid, sulfuric acid, and sodium nitrate were reported in P/M TRIs, though the quantities of ammonia and inorganic compounds are not significant as either air releases or transfers off-site

## **6.6 TARGETS OF OPPORTUNITY FOR IMPROVED ENERGY AND RESOURCE EFFICIENCY**

There are two distinct routes through which improved energy and resource efficiency can be achieved in the P/M industry. First, opportunities to improve the energy and resource efficiency in P/M processes provide direct gains in overall efficiency. In the *PM<sup>2</sup> Industry Vision and Technology Roadmap*, the industry established goals of reducing energy consumption by 50 percent by 2010 and 80 percent by 2020. These aggressive industry goals imply the existence of significant opportunities to improve the energy efficiency of P/M processes. Such opportunities are most likely in the powder manufacturing and sintering process steps, as they are the most energy-intensive steps.

Energy and resource efficiency gains can also be realized in applications where components made by competing metal forming processes such as casting, extrusion, hot forging, and machining can be replaced by components made via P/M, an inherently more efficient process. Accordingly, efforts to improve the properties of P/M components (e.g., through higher component densities) can provide energy and resource efficiency gains by enabling P/M to replace more energy-intensive processes. This section describes some technology developments, trends, and opportunities for improving both the efficiency of P/M processes and enhancing the properties P/M components can achieve.

### **U.S. P/M INDUSTRY WORKS TOWARDS GREATER EFFICIENCY AND APPLICATIONS**

The P/M Industry Roadmap Strategy Board has established a priority project “short list” that describes the industry’s priorities for research and development. All of the priorities directly relate to either improving the efficiency of the P/M process or broadening the potential applications in which P/M is a viable metal forming option. The list includes:

- Manufacture of full density, high-tolerance components using single pressing and sintering techniques
- Development of predictive tools that can describe component properties and performance more quickly (math-based component design, processing, and validation)
- Advanced material manufacture using novel materials such as nanoscale iron powder

- Development of sensor-based feedback control techniques to reduce process variation
- Three-dimensional forming techniques for complex shapes
- Electromagnetic circuit design with three-dimensional P/M magnets and core components
- Improved joining of P/M components for increased functionality

The U.S. P/M industry has funded various R&D programs through the Center for P/M Technology (CPMT) to provide more property and process information to design engineers. These studies are focused on developing design data so that end-users in several markets, most notably automotive, will consider P/M as a design option. This work allows automotive design engineers to consider P/M in addition to other component production options, opening up the range of potential automotive applications. This leads to energy savings in several ways: first, expanding the applications for P/M in automobiles creates efficiency gains due to P/M efficiency advantage; and second, P/M components often offer weight savings, thus reducing energy consumption.

#### **ANNUAL TECHNOLOGY TRENDS ARTICLE HIGHLIGHTS ADVANCES IN P/M INDUSTRY**

For the past several years, Peter Johnson, Director of Public Relations and Government Affairs at MPIF, has published an annual paper in the *International Journal of Powder Metallurgy* that outlines recent technology developments and trends. These papers offer a thorough review of key technological developments throughout the three main industry sectors: powder manufacturing, tooling and equipment supply, and component production. The reviews include developments in press and sinter, MIM, isostatic pressing, and powder forging. While the articles are primarily focused on market-driven advances, some of the trends and developments reported relate to energy- and resource-efficiency enhancements.

The U.S. P/M industry continues to invest in new technology to improve the properties of P/M parts and products, and the efficiency of P/M operations. For conventional P/M, the overall goal is to match the properties of wrought materials (see Figure 6-10 for component production statistics). Warm compaction and other high-density forming processes and new materials are aimed at increasing tensile strength, fatigue, and elongation.

#### **POWDER PROCESSING**

Metal powder manufacturers are continuously upgrading their materials and investing in new processes and bonding technology to enhance high-strength performance and tolerances. Powder processing capabilities have been extended to include alloying techniques such as prealloying, admixing, diffusion bonding and binder treatment. This allows the characteristics of

base powders and press-ready mixes to be tailored to meet specific applications. Powder mixing technology is being developed to increase the green strength of P/M parts to values twice as high as those obtained with conventional lubricants, which is combined with improved powder compressibility, an important feature for high-density parts. Another trend in powder availability is aimed at cost reduction in areas such as green machining and sinter-hardening.

Sinter-hardening represents one of the most recent novelties in ferrous P/M. This process exploits the natural high hardenability of ferrous alloys to get hard microconstituents immediately after cooling inside a suitable sintering furnace. Studies have been done to understand ideal sintering furnace temperature profiles (Bocchini, et al., 2001), and ongoing work in this area can lead to more extensive use of sinter-hardening for ferrous materials.

### **PRESSES**

P/M equipment makers are investing in new technology and producing larger presses with improved controls and tooling materials. Hybrid presses combine the speed and accuracy of a mechanical press with the control of a hydraulic system to produce larger parts at competitive production rates. There is a definite trend in the industry towards more complexity in parts, which has led to additional motions in presses. Automatic press programs are being developed to optimize movements to meet size, density, and weight requirements at optimum speeds with minimal operator input. Hydraulic presses are being outfitted with new generation hydraulics which allow cycles similar to hybrid presses. Such advances enhance the range of applications where P/M can be used, often replacing more energy- and resource-intensive processes.

### **SINTERING FURNACES**

Sintering furnace manufacturers are providing furnaces that meet more stringent production requirements, such as temperature uniformity and vacuum/atmosphere controls. Higher-temperature sintering, for higher densities and improved properties, is also a strong trend in the United States. Some opportunities for improving energy efficiency in sintering furnaces are achievable through careful control of temperature uniformity and atmospheric consumption.

### **THEORETICAL VS. ACTUAL ENERGY REQUIREMENTS SUGGEST SINTERING OPPORTUNITIES**

The theoretical energy requirements for P/M processes, presented in Table 6-4, indicate energy efficiency opportunities in all P/M processes. As calculated by Bocchini, the so-called technological efficiency (difference between theoretical minimum and actual energy consumption) ranged from 15 to 59 percent, indicating significant opportunities to improve energy efficiency in

almost all steps of P/M component production. However, because sintering is by far the most energy intensive step in component manufacturing, this process offers the greatest opportunity for improving energy efficiency. In fact, Bocchini states that “only small improvements appear to be possible for powder production processes, whereas a great many possibilities are open for improving P/M furnaces.” This conclusion appears as valid today as it was 20 years ago.





# 7. WELDING

## 7.1 INDUSTRY OVERVIEW

Welding is a joining process that uses heat, pressure, or both to fuse the surface of two distinct elements and form a single unit. Joining techniques encompassed by this definition include fusion welding, solid-state welding, weld-bonding, diffusion welding, brazing, and soldering. Over 100 processes comprise the family of welding technologies, which includes methods for welding metals, polymers, and ceramics, as well as emerging composite and engineered materials.

The “welding industry” encompasses the workforce that performs welding operations; the welding supply industry that provides the equipment, products, consumables, and services needed by the workforce; and the end-users in the larger national and international industrial sector who use welding and joining processes to manufacture their products.

Welding is critical to a variety of applications. Table 7-1 lists some various economic sectors that employ welding processes, along with example applications in each.

**TABLE 7-1. EXAMPLE WELDING APPLICATIONS**

Sector	Characteristic Applications
Automotive	All vehicle and trailer manufacturing; automotive systems and parts manufacturing; motorcycle and bicycle manufacturing; automotive exhaust system repair
Aircraft/ Aerospace	Aircraft manufacturing; aircraft parts and systems manufacturing; missile and space vehicle manufacturing; missile and space vehicle parts and systems manufacturing
Electronics/ Medical	Electronic components; electronic instruments/equipment; office and communications equipment; medical instruments and equipment
Light Industrial Manufacturing	Industrial/lawn/garden tractors; materials handling equipment; industrial tools; heating and ventilation; fluid, power, and air transmission equipment; valves and fittings; light gauge building components; pipes and tubing; service industry machinery; household appliances; miscellaneous fabricated metal products
Heavy Industrial Manufacturing	Construction and mining machinery; farm machinery and equipment; shipbuilding and repair; railroad rolling stock; military armored vehicles; engine, turbine, and power transmission equipment; power boiler, heat exchanger, and heavy tank manufacturing; industrial machinery; oil and gas field machinery
Construction	Industrial buildings; commercial buildings; bridge & tunnel construction; pipeline construction; structural steel erection; fabricated structural metal products; welding repair establishments; other heavy construction
Capitalized Repair & Maintenance	Oil and gas production and distribution; petroleum and coal products; primary metals industries (e.g., steel, aluminum); metal forging and stamping; mining operations; electrical power generation; paper production

SOURCE: WELDING-RELATED EXPENDITURES, INVESTMENTS, AND PRODUCTIVITY MEASUREMENT IN U.S. MANUFACTURING, CONSTRUCTION, AND MINING INDUSTRIES, 2002.

Welding energy and environmental data for this profile will be considered primarily in relation to U.S. industrial manufacturing applications, as opposed to sectors with less of an industrial emphasis, such as construction and electronics/medical equipment manufacture. Thus, from the categories listed in Table 7-1, automotive, aircraft/aerospace, light industrial manufacturing, and heavy industrial manufacturing are the chief areas of concern.

The capitalized repair and maintenance applications listed in Table 7-1, despite their clear relevance to U.S. manufacturing, receive minimal emphasis in this report because welding is not a critical process step in the typical day-to-day operations of these industries (e.g., oil production, ore extraction, metal fabrication, etc.)—the welding-related operations in these applications are specific to maintenance. Moreover, welding-related energy costs in this sector account for only 0.2 percent of total energy costs in these industries (AWS, 2002).

## **7.2 INDUSTRY PERFORMANCE AND MARKET TRENDS**

Most manufacturers that employ welding as a critical fabrication step have only a minimal understanding of the economics associated with its use. Additionally, only a small minority of firms have evaluated the importance of welding throughout the manufacturing process. U.S. entities that have given significant consideration to the entire manufacturing process are most competitive with similar international outfits. By understanding the costs associated with welding and its value-added throughout production, firms can improve productivity and increase the ultimate value of the manufactured product. (AWS, 2002).

Welding expenditures represent a substantial contribution to the U.S. economy. Many industries that employ welding processes provide the backbone for our nation's defense, infrastructure, and economic well-being. Revenue from these industries totaled over \$3.1 trillion in 2000, representing roughly one-third of the total U.S. GDP. In 2000, welding-related expenditures exceeded \$34 billion, equivalent to more than \$325 for every household in the United States (AWS, 2002). To put this in a different perspective, this figure would rank the welding industry at number 41 in the Fortune 500, and is greater than the GDP of two-thirds of the world's nations (Remich, 2003).

Labor costs represent 70 percent of total U.S. welding-related expenditures, exceeding those of all other welding expenses. Though less significant, welding-related energy expenditures amounted to more than \$1.1 billion in 2000, and spending on welding materials and consumables, not including equipment, totaled \$8.3 billion that same year (AWS, 2002).

As shown in Table 7-2, total costs of welding specific to manufacturing – including capital purchases, materials, consumables, labor, energy, and purchased services – were approximately \$17 billion in 2000.

**TABLE 7-2. 2000 WELDING-RELATED EXPENDITURES BY TYPE (IN MILLIONS)**

Industrial Sector	Total Expenditures	Labor	Materials & Consumables	Energy	Capital	Other Costs
Heavy Industrial Manufacturing	\$7,630	\$5,440	\$1,670	\$221	\$245	\$51
Light Industrial Manufacturing	\$5,380	\$3,360	\$1,210	\$175	\$565	\$73
Automotive & Aircraft/Aerospace	\$4,000	\$2,030	\$537	\$131	\$1,260	\$37
<b>Total</b>	<b>\$17,010</b>	<b>\$10,830</b>	<b>\$3,417</b>	<b>\$527</b>	<b>\$2,070</b>	<b>\$161</b>

SOURCE: WELDING-RELATED EXPENDITURES, INVESTMENTS, AND PRODUCTIVITY MEASUREMENT IN U.S. MANUFACTURING, CONSTRUCTION, AND MINING INDUSTRIES, 2002.

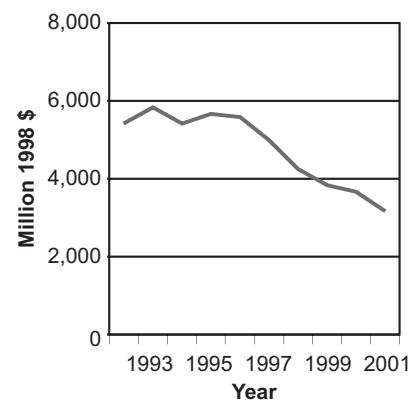
In 1996, nearly 500,000 Americans were employed as welders, cutters, and welding machine operators. Additionally, 25 other trades (e.g., ironworkers, boilermakers, pipefitters) or occupations (e.g., precision assembly, shipfitting) were employed where welding was either a specialized skill or an integral part of the operation. When including the workers from these professions, the size of the welding community surpasses two million workers – more than 10 percent of the U.S. manufacturing workforce (BLS, 1996).

Machinery, filler materials, and accessories for the various welding processes are manufactured and supplied by fewer than 10 large companies whose sales exceed \$100 million. Several hundred much smaller companies specialize in items such as welding torches, welders' helmets, hammers, marking equipment, welding screens, special fluxes, and so forth.

As shown in Figure 7-1, between 1997 and 2001 the value of shipments for welding and soldering equipment manufacturers decreased at an average rate of 10.5 percent per year. During this same period, employment for this sector remained relatively constant, averaging over 20 thousand employees. In 2001, welding and soldering equipment manufacturers had a total value of shipments of \$4 billion dollars, employing 18,000 people (DOC, 2002).

In 2001, exports of welding and soldering equipment totaled \$741 million dollars, a 28 percent decline from the previous year. The total value of imports decreased by 3.3 percent to \$702 million. However, a positive trade balance of \$34 million was achieved (see Table 7-3 for details).

**FIGURE 7-1. VALUE OF SHIPMENTS – WELDING/SOLDERING EQUIPMENT, 1992-2001 (MILLION 1998 \$)**



SOURCE: INTERNATIONAL TRADE ADMINISTRATION INDUSTRY STATISTICS (ADJUSTED FOR INFLATION WITH U.S. CENSUS BUREAU IMPLICIT PRICE DEFLATORS).

**TABLE 7-3. WELDING AND SOLDERING EQUIPMENT MANUFACTURING TRADE DATA (MILLION 1998 DOLLARS)**

	1997	1998	1999	2000	2001
Value of exports	1,274	1,055	1,075	1,040	741
Value of imports	1,010	839	680	726	702
Trade Balance	265	216	395	314	39

SOURCE: INTERNATIONAL TRADE ADMINISTRATION INDUSTRY STATISTICS (ADJUSTED FOR INFLATION WITH U.S. CENSUS BUREAU IMPLICIT PRICE DEFLATORS).

A key driver for the U.S. welding industry in the coming years is the potential for increased globalization of businesses and markets for materials fabrication. The U.S. industry will feel the effects of increased foreign competition as its companies begin to use suppliers and gain customers from around the world.

Another important determinant of the welding industry's future is the drive to improve productivity. Future welding processes will be based on rigorous engineering analysis, numerical modeling, and computer-based automated manufacturing, depending heavily on information technology. Similarly, information technology will be important as welding markets become increasingly international—to help incorporate cost-saving business practices and increase productivity both here and abroad. The welding industry will work to address concerns regarding limitations of materials, process, and ability to ensure quality.

New regulations and standards may be imposed by government to limit industrial energy use and environmental impact. Such mandated constraints will affect competitive selections among joining choices. The U.S. welding industry will seek opportunities to lead technological developments that will allow faster and more flexible fabrication of new products (AWS, 1999).

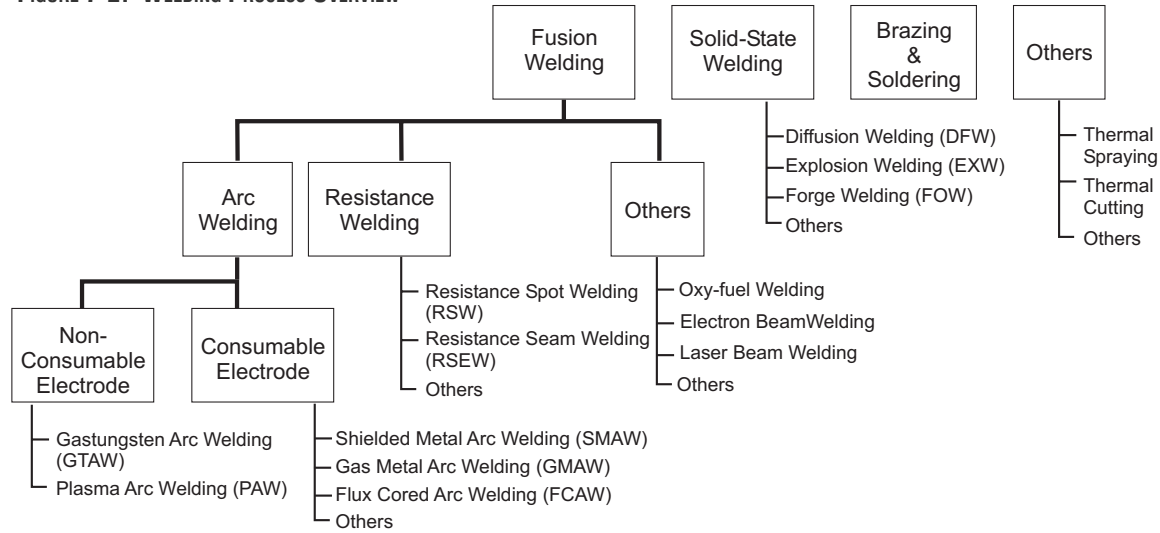
### 7.3 WELDING PROCESSES

There are numerous welding processes to join and cut metals. As shown in Figure 7-2, these processes are divided into two broad classes: fusion welding and solid-state welding, with the remainder of thermal joining processes falling under brazing and soldering (ASM, 1998).

#### 7.3.1 FUSION WELDING

Fusion welding processes involve localized melting and solidification and are normally used when joining similar material combinations or materials belonging to the same family. Most fusion welding is accomplished via electric arc welding techniques, which represent an estimated 90 percent of all industrial welding. Generally, it is found that heat source power densities of approximately 1,000 watts/cm<sup>2</sup> are needed to melt most metals (ASM,

FIGURE 7-2. WELDING PROCESS OVERVIEW

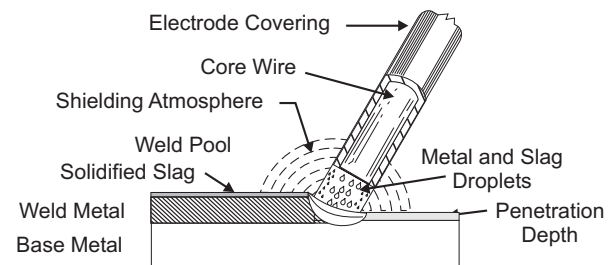


SOURCE: U.S. EPA WELDING DOCUMENT.

1998). The major industrial fusion welding processes include shielded-metal arc welding, gas metal arc welding, flux cored arc welding, gas tungsten arc welding, and plasma arc welding. Resistance welding and other processes account for the remaining fusion arc welding procedures.

**Shielded metal arc welding (SMAW)**, also known as Manual Metal Arc (MMA) or stick welding, is the most common welding procedure. Like all electric arc welding techniques, SMAW produces a coalescence of metals by heating them with an arc between a metal electrode and the workpieces. The electric arc is maintained between the welding joint at the surface of the base metal and the tip of the covered welding electrode (ASM, 1998).

FIGURE 7-3. SMAW PROCESS



SOURCE: U.S. EPA WELDING DOCUMENT.

During operation, the core rod conducts electric current to produce the arc and provide filler metal from the electrode for the joint. The electrode covering provides stability to the arc and protects the molten metal through the creation of shielding gases as it vaporizes while the workpieces move through the arc. Figure 7-3 illustrates this process (EPA, 1994). Shielding gases serve the important function of preventing atmospheric contamination of the weld.

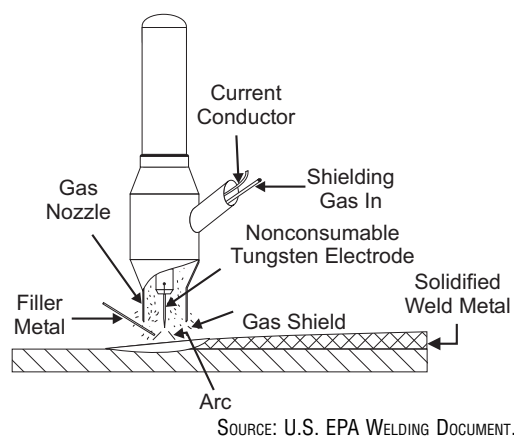
Electrode composition is generally similar to that of the weld metals. The popularity of this process stems from its relatively low equipment cost, versatility (it can be used in all positions—horizontally, vertically, flat, and overhead), simplicity, base-metal thickness tolerance, and a wide variety of readily available electrode materials.

**Gas metal arc welding (GMAW)** is perhaps the second most common electric arc welding technique. The process is a derivative of SMAW and heats the materials using similar means, though shielding is obtained entirely from an externally supplied gas. GMAW is alternatively referred to as Metal Inert Gas (MIG) or Metal Active Gas (MAG) welding, depending on the nature of the supplied shield gas. Instead of using a covered electrode tube to create the welding arc between the electrode and weld metals, a consumable filler electrode (often in wire form) is fed continuously through a guide to achieve the same result (ASM, 1998).

The popularity of this welding process has increased steadily in the United States and elsewhere over the last 25 years (Pekkari, 2000). GMAW is the only form of consumable electrode welding that can be used to join all commercially important metals, such as carbon steel, high-strength low-alloy (HSLA) steel, stainless steel, nickel alloys, titanium, aluminum, and copper. GMAW offers higher deposition and weld rates than SMAW, and can be performed in machine, automatic, or semiautomatic modes. The equipment is generally more costly and complex than that used in SMAW (EPA, 1994).

**Flux cored arc welding (FCAW)**, a derivative of GMAW, joins base and weld metals by heating them with an arc between a continuous tubular (versus solid) filler-metal electrode and the workpieces. A flux contained within the electrode, released as the electrode is consumed, shields the weld. Shielding may be supplemented via the addition of an externally supplied gas or gas mixture.

**FIGURE 7-4. GTAW PROCESS**



**Gas tungsten arc welding (GTAW)**, also known as Tungsten Inert Gas (TIG) Welding, is another commonly used precision arc welding process (Figure 7-4). A welding arc is established between a tungsten electrode and the part to be welded. The metal of the part is melted and fused by the intense heat of the arc. Shielding is obtained via the addition of a gas or gas mixture. The application of pressure and the addition of filler metal to the process to facilitate the weld or to achieve certain weld properties are both optional.

**Plasma arc welding (PAW)**, basically an advancement of the GTAW process, uses a copper nozzle to surround the tungsten electrode. A pilot arc is first established between the electrode and copper nozzle and then transferred to the part to be welded. Shielding is obtained from ionized gas dispensed from an orifice surrounding the electrode and may be supplemented through the addition of a separate shielding gas. As with GTAW, externally applied pressure and filler metals are optional. Unlike SMAW, GMAW, and FCAW, the

electrode used to create the welding arc during GTAW and PAW is not consumed during the welding process.

**Resistance welding** generates heat for welding via the resistance of an electrical current through the parts being joined. Resistance welding is most commonly used to weld two overlapping sheets or plates. A pair of electrodes conduct electrical current to the joint, and a weld is subsequently formed as the mating surfaces are heated. The electrode pair clamps the sheets under pressure to provide good electrical contact and to contain the molten metal in the joint. High currents are required to create sufficient resistance heat and melt the base of the metal rapidly. A single resistance weld is typically made in less than one second. This low-cost, high-rate process has proven particularly valuable in the automotive industry as a substitute for the riveting of thin metal members (ASM, 1998).

Other types of fusion welding include oxyfuel gas welding (combustible gases heat and melt the base metal without a welding electrode), electron beam welding (fusion process performed in a vacuum chamber where a high velocity beam of electrons is focused on the surface to be welded), laser beam welding (focused coherent light, a laser, melts the base material), and percussion welding.

### **7.3.2 SOLID STATE WELDING**

Solid-State Welding (SSW) processes, far less common than their fusion welding counterparts, produce a coalescence of surfaces at temperatures below the melting point of the base metal being joined and without the addition of brazing or solder filler metal. These processes use deformation, or diffusion coupled with limited deformation, to produce joints between similar and non-similar materials. Pressure may or may not be applied. Types of solid-state welding include diffusion welding, explosion welding, forge welding, cold welding, roll welding, and friction welding (ASM, 1998).

### **7.3.3 BRAZING AND SOLDERING**

Brazing and soldering comprise the third major classification of welding processes. Brazing joins solid metals by introducing a liquid metal that melts above 840°F. Brazing can produce strong, uniform, and leakproof joints rapidly and inexpensively. Similarly, soldering joins two solid metals by melting a filler metal (solder) below 840°F. While the metals remain solid, the solder is distributed between the surfaces of the joint by capillary action (ASM, 1998).

## **7.4 ENERGY AND MATERIALS CONSUMPTION**

Energy consumption – chiefly electrical – accounts for a small percentage of industrial welding-related costs, as was shown above in Table 7-2. Though



energy use is slightly above three percent of welding-related production expenditures (total costs minus capital investment expenses) in these sectors, it translates into a significant annual energy consumption of nearly 130 trillion Btu for industrial purposes. Materials costs, such as those for electrode materials, weld metals, filler metals, and shielding gases/gas mixtures, were more than six times as high as energy costs for these three industry groups. Table 7-4 relates these data by industrial sector, though in different terms than previously.

**TABLE 7-4. FY00 WELDING ENERGY USE AND RELATIVE ENERGY & MATERIALS COSTS**

Industry	Energy Use (10 <sup>12</sup> Btu) <sup>1</sup>	Energy Costs (% of total production costs) <sup>2</sup>	Materials Costs (% of total production costs) <sup>2</sup>
Heavy Industrial Manufacturing	54	3.0	22.6
Light Industrial Manufacturing	43	3.6	25.1
Automotive & Aircraft/Aerospace	32	4.8	19.7
<b>Total</b>	<b>129</b>	<b>3.5</b>	<b>22.6</b>

<sup>1</sup> Metric obtained using the electricity price as set forth in the spreadsheet analysis model for reporting project results in accordance with the Government Performance and Results Act of 1993 (GPRA).

<sup>2</sup> Total production costs = total expenditures - capital investments. Alternatively, total production costs = energy costs + materials/consumables costs + labor costs + other costs. Formula taken from table data source.

SOURCE: REPORT ON WELDING-RELATED EXPENDITURES, INVESTMENTS, AND PRODUCTIVITY MEASUREMENT IN U.S. MANUFACTURING, CONSTRUCTION, AND MINING INDUSTRIES.

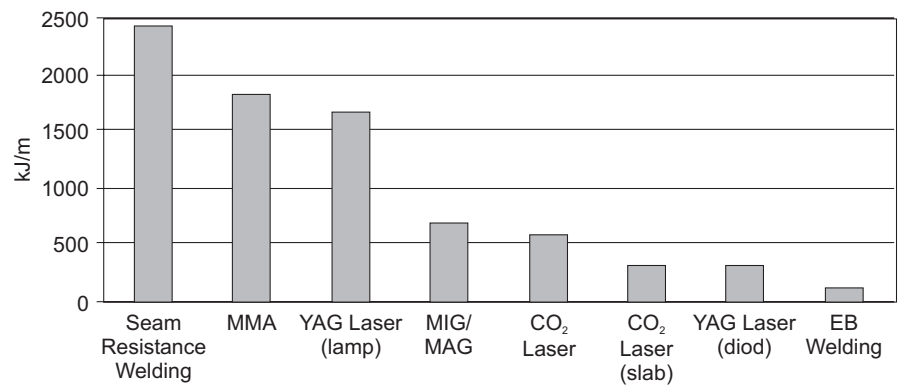
#### 7.4.1 ENERGY CONSUMPTION

Energy efficiency varies substantially depending on the welding technique employed. However, when choosing a welding method, the method of heat input is an important factor; too much heat input reduces the impact strength of the joint and causes thermal stress and distortion in the workpiece. As a rule of thumb, welding processes with the highest energy density, such as laser welding, often have the lowest heat input. This factor, coupled with higher throughput capabilities, helps compensate for the lower power source efficiencies these processes typically demonstrate. Consequently, despite the relatively low efficiency of laser welding, it can compete with more traditional methods like SMAW. Figure 7-5 illustrates the characteristic energy efficiencies of several welding types when joining 4mm steel plate, taking into account power losses from equipment (Weman, 1999).

Power sources also play a large role in determining welding energy efficiency. Typical efficiency values for arc welding power sources are 75 to 85 percent. This value varies depending on the type of power source used. Generally, inverter power supplies are the most efficient, followed by transformers and converters. The differences in power source efficiencies originate from the amount of open circuit losses when the equipment is not in use; an old rotating welding converter could have open circuit losses of more than 1 kW,

a large MMA welding machine 300-400W, and an inverter power source less than 50W. When choosing a power source for industrial welding, high efficiency is a critical economic factor. Though energy is a minor fraction of total welding costs, energy costs can be sufficient to justify more expensive energy-saving equipment (Weman, 1999).

FIGURE 7-5. REQUIRED ENERGY PER METER FOR DIFFERENT WELDING METHODS



SOURCE: PEKKARI, 1999.

#### 7.4.2 MATERIALS CONSUMPTION

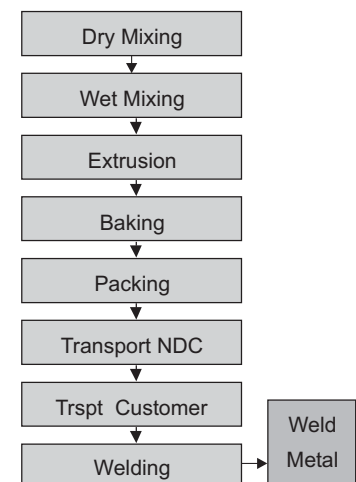
Welding materials represent a significant expense to welding firms, with a large variety in use. These materials fall under two main categories: electrodes/filler metals and shielding gases.

Because electrodes (in some cases) and filler metals are often made of similar materials to those being welded, their composition varies widely by process.

Commonly used filler and flux materials in electrodes and wires include metals such as zinc, silver, chromium, nickel, manganese, copper, iron, lead, and aluminum. Expenditures for these raw materials are roughly double those for gases and gas mixtures (Weber, 2003). In the United States in 1999, approximately 380,000 tons of weld metal were deposited using solid and cored wires in electric arc welding (Pekkari, 2000a). The production of electrode weld metal consists of numerous process steps, as can be seen in Figure 7-6.

Shielding gases are not a major cost, but they can influence many steps of the weld. Optimally, shielding gases should be as non-oxidizing as possible (e.g., lowering CO<sub>2</sub> content in the commonly used CO<sub>2</sub>-argon gas mixture). Lower CO<sub>2</sub> levels reduce fumes, smoke, and spatter, and allow the mixture to be used for more high-speed welding options, while 20 percent CO<sub>2</sub> or higher causes problems. To reduce gas use, regular inspection of the gas distribution systems is recommended, and control of weld size is another effective means for reducing both gas and metal consumption (Weber, 2003).

FIGURE 7-6. LIFE-CYCLE ANALYSIS PROCESS TREE FOR 1-KG OF ESAB SMAW ELECTRODE<sup>1</sup>



<sup>1</sup>OK 48.00, 3.25-mm diameter electrode manufactured by ESAB AB of Gothenburg, Sweden.

SOURCE: PEKKARI, 1999.

#### 7.5 ENVIRONMENT

The primary environmental concern for welding operations is emissions, particularly from a worker health and safety standpoint. Many of the fumes released during welding processes are extremely hazardous. Consequently,

welding plants often go to extensive lengths to ensure adequate workspace ventilation and toxic fume evacuation. This concern also provides incentive to use fully automated procedures when possible. Fume content depends largely on the joining process used, the materials being welded, and the flux/filler metal being used. Table 7-5 provides a summary of typical emissions associated with a variety of welding-related joining methods.

**HAZARDOUS AIR POLLUTANTS  
LISTED IN 1990 CLEAN AIR  
ACT AMENDMENTS**

- Manganese
- Nickel
- Chromium
- Cobalt
- Lead

### 7.5.1 Air Emissions

The main air emissions released during welding operations are particulate matter and particulate phase hazardous air pollutants. Typically, electric arc welding is the only welding process that generates pollutants in large enough quantities to cause concern. Resistance welding may also generate hazardous pollutants when using certain electrodes or workpiece compositions. Fewer fumes are released during other welding procedures due to the lower process temperatures.

**TABLE 7-5. WELDING-RELATED EMISSIONS AND BYPRODUCTS**

Joining Method	Environmental Output	Adverse Effects
Welding	<ul style="list-style-type: none"> <li>• Emission of radiant energy (light, heat)</li> <li>• Production of slag and residuals of welding materials</li> <li>• Emission of fumes, containing metal oxides, metallic elements, and gases (NO<sub>x</sub>, O<sub>3</sub>)</li> </ul>	<ul style="list-style-type: none"> <li>• Surrounding pollution</li> <li>• Ground pollution with metals and their components</li> <li>• Atmospheric pollution with metals, vapors, gases, and particulate substances</li> </ul>
Soldering	<ul style="list-style-type: none"> <li>• Emission of hydrogen bromide, lead oxide, hydrogen chloride, formaldehyde, inorganic tin compounds, organic tin compounds, and washing liquids</li> </ul>	<ul style="list-style-type: none"> <li>• Atmospheric pollution with metals, vapors, gases, and particulate substances</li> <li>• Ground pollution</li> </ul>
Brazing	<ul style="list-style-type: none"> <li>• Emission of boron oxide, boron trifluoride, cadmium oxide, fluorides, copper oxide, phosphorous pentoxide, silver oxide, and zinc oxide</li> </ul>	<ul style="list-style-type: none"> <li>• Atmospheric pollution with metals, vapors, gases, and particulate substances</li> </ul>
Flame Spraying	<ul style="list-style-type: none"> <li>• Emission of metallic oxides (based on powder composition used)</li> <li>• Emission of NO<sub>x</sub></li> </ul>	<ul style="list-style-type: none"> <li>• Atmospheric pollution with metals, vapors, gases, and particulate substances</li> </ul>
Arc Spraying	<ul style="list-style-type: none"> <li>• Emission of metallic oxides (based on powder composition used)</li> </ul>	<ul style="list-style-type: none"> <li>• Atmospheric pollution with metals, vapors, gases, and particulate substances</li> </ul>
Plasma Spraying	<ul style="list-style-type: none"> <li>• Emission of metallic oxides (based on powder composition used)</li> </ul>	<ul style="list-style-type: none"> <li>• Atmospheric pollution with metals, vapors, gases, and particulate substances</li> </ul>
Plasma Spraying of Chromium-Nickel Powder	<ul style="list-style-type: none"> <li>• Emission of metallic oxides (based on powder composition used)</li> <li>• Emission of nickel oxide</li> <li>• Emission of O<sub>3</sub></li> </ul>	<ul style="list-style-type: none"> <li>• Atmospheric pollution with metals, vapors, gases, and particulate substances</li> </ul>

SOURCE: PEKKARI, 2002.

## HAZARDOUS METALS IN WELDING FUMES

The quantity of emissions released depends largely on the type of welding process used, electrode composition and size, and workpiece composition. Table 7-6 summarizes emissions by welding process and weld material. Additionally, coatings on the workpiece can generate organic and metallic fumes (e.g., galvanized coatings, cleaners, oils, etc.), depending on the particular application. Operating conditions that influence fume emissions include travel speed, voltage, current, arc length, polarity, welding position, electrode angle, and deposition rate (EPA, 1994).

**TABLE 7-6. TYPICAL WELDING-RELATED EMISSIONS BY PROCESS AND MATERIAL**

Welding Process	Low-alloyed Steel	High-alloyed Steel	Aluminum Alloys	Nickel Alloys
SMAW	Particulate fumes (Cr, Mn, Cu, other metal oxides); F; NOx; CO	Particulate fumes (Cr, Mn, Cu, other metal oxides); NOx; CO; Cr(VI); Ni	N/A	Particulate fumes (Cr, Mn, Cu, other metal oxides); NOx; CO; Ni
FCAW	Particulate fumes (Cr, Mn, Cu, other metal oxides); NOx; CO	Particulate fumes (Cr, Mn, Cu, other metal oxides); NOx; CO; Cr(VI); Ni	N/A	Particulate fumes (Cr, Mn, Cu, other metal oxides); NOx; CO; Ni
MIG/MAG	Particulate fumes (Cr, Mn, Cu, other metal oxides); NOx; CO; CO <sub>2</sub> <sup>1</sup>	Particulate fumes (Cr, Mn, Cu, other metal oxides); NOx; CO; Cr(VI); Ni; CO <sub>2</sub> <sup>1</sup>	Particulate fumes (Cr, Mn, Cu, other metal oxides); NOx; CO; CO <sub>2</sub> <sup>1</sup>	Particulate fumes (Cr, Mn, Cu, other metal oxides); NOx; CO; CO <sub>2</sub> <sup>1</sup>
TIG	ThO <sub>2</sub> <sup>2</sup>	Cr(VI); Ni oxides; ThO <sub>2</sub> <sup>2</sup>	N/A	Ni oxides
Submerged Arc Welding (SAW)	Residuals of welding materials	Residuals of welding materials	N/A	Residuals of welding materials
Plasma Welding	Particulate fumes (Cr, Mn, Cu, other metal oxides); CO	Particulate fumes (Cr, Mn, Cu, other metal oxides); CO; Cr(VI); Ni oxides	Particulate fumes (Cr, Mn, Cu, other metal oxides); CO	Particulate fumes (Cr, Mn, Cu, other metal oxides); CO; Ni oxides
Oxyfuel Welding	Particulate fumes (Cr, Mn, Cu, other metal oxides); NOx	N/A	N/A	N/A
Resistance Welding	CO	CO	CO	CO

<sup>1</sup> Applicable to MAG welding.

<sup>2</sup> Applicable when thoriated electrodes are used.

SOURCE: PEKKARI, 2002.

The welding fume is formed by the vaporization and subsequent recondensation of metallic elements upon cooling in ambient air. Consequently, the particulate matter produced is generally submicron in size and is considered to be PM-10. Although air pollutants are generated during welding operations, little information is available on the gases produced. Known gaseous pollutants released in some welding processes include CO<sub>2</sub>, CO, NO<sub>x</sub>, and O<sub>3</sub>.

Many site and operator variables play important roles in the amount of fume produced, including the type of welding in use. Typically, for the electric arc welding processes, submerged arc welding has the lowest fume emissions, while FCAW has the highest. Sample elemental fume chemistries for fume emissions of iron and reportable elements for several general electrode types used in three common arc welding methods are shown in Table 7-7. Emissions vary depending on class of electrode used.

**TABLE 7-7. ELEMENTAL FUME CONTENT OF ARC WELDING PROCESSES**

Process	Electrode Type	%Converted to fume	% Fe	% Mn	% Cr	% Ni	% Other
GMAW	Solid wire (Mild steel)	0.6	63.0	7.7	—	--	0.6 (Cu)
	Metal Cored Wire (Steel)	1.2	58.1	5.4	—	—	—
	Solid Wire (Stainless steel)	0.5	38.0 <sup>1</sup>	8.7	12.5	5.1	—
	Solid Wire (Al)	2.0	<0.01	<0.01	--	--	48.0 (Al)
SMAW	Manual Electrode (Mild steel)	2.6	46.0	4.0	—	—	—
	Manual Electrode (Stainless steel)	0.6	7.8	5.9	5.0	0.6	--
FCAW	Cored Wire (Steel, Gas shielded)	1.2	43.1	8.6	—	—	—
	Cored Wire (Steel, Self-shielded)	2.6	19.0	1.5	—	—	—

<sup>1</sup> Aluminum is the dominant elemental component.

SOURCE: AWS, 2003.

Other variables that affect emissions include current, arc voltage, arc length, travel speed, and welding electrode angle. Lowering current and voltage decreases the amount of fume generated, while maintaining the welding angle close to perpendicular can also decrease the fume emissions (EPA, 1994).

### **CAPTURE AND COLLECTION OF EMISSIONS**

For automated welding processes, emissions are captured by forced air removal. Manual welding processes often use portable ducts or hoods. Another method to capture emissions is torch fume extraction. The extracting duct, mounted on the torch, removes the fume directly from the work area.

The captured emissions are vented to a collector, which removes the particulate and organic gases. Typically, the particulate is removed with a high efficiency filter or electrostatic precipitator, with the organic gases removed by adsorption with activated carbon. Particulate scrubbers are also used (EPA, 1994).

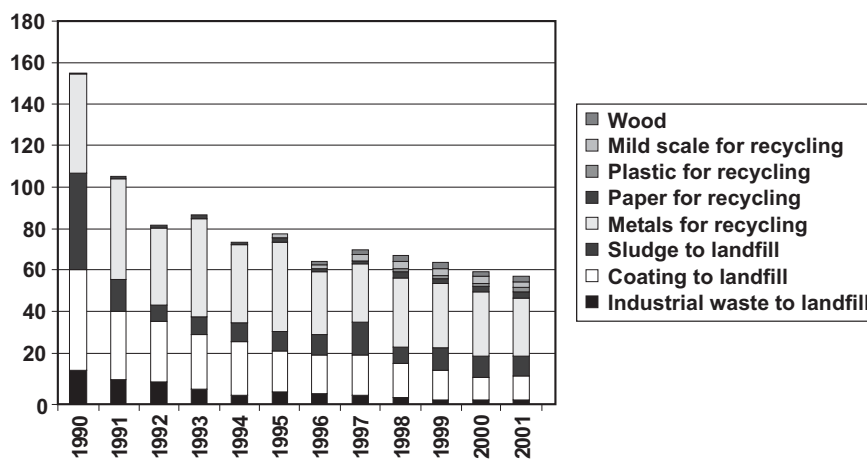
### 7.5.2 EFFLUENTS

There are no significant effluents resulting from welding and welding-related processes.

### 7.5.3 WASTES, RESIDUALS, AND BY-PRODUCTS

As shown earlier in the life-cycle assessment (Figure 7-6), electrode production in particular is a highly resource-intensive process. Over the last ten years, due to increasingly strict environmental regulations and environmental management agreements such as ISO 14001, the welding industry has shown a 60 percent decrease in total wastes resulting from electrode production. Figure 7-7, inclusive of all relevant materials (e.g., electrode shipping and packing products), displays this continuous trend.

FIGURE 7-7. SOLID WASTE FROM ELECTRODE PRODUCTION (KG/TON MANUFACTURED)



SOURCE: PEKKARI, 2002.

Suppliers must find better ways to package products, as concerns increase regarding the amount of packaging material used, which then results in waste. The stubs of electrodes are another issue, though this is a difficult concern to address in an economical manner. Although the generated slag can be reused by manufacturers of consumable electrodes, the return cost for the residual material is considered too high. Currently, the least expensive method for disposing of electrode slag is to landfill the material, provided it does not contain any restricted substances (Pekkari, 2002b).

## **7.6 TARGETS OF OPPORTUNITY FOR IMPROVED ENERGY & RESOURCE EFFICIENCY**

### **7.6.1 INDUSTRY VISION ENERGY & ENVIRONMENTAL GOALS**

The industry vision, published in 1999, proposes to reduce energy use by 50 percent through productivity improvements such as decreased pre- and post-heating operations; use of advanced, lower heat input welding processes; and less over-welding.

### **7.6.2 WELDING INDUSTRY ROADMAP**

The *Welding Industry Roadmap* was created in 2001 by major end-users, researchers, and welding equipment manufacturers as a strategic research and development plan to achieve the goals set forth in the industry *Vision*. The industry intends to reduce cost and expand the use of welding by employing non-traditional processes, alternative energy sources, automation/robotics, and reduced post-weld processing. The industry also plans to minimize the impact of welding on natural resources through reduced materials and energy consumption.

New welding processes and filler metals will improve productivity and reduce emissions of toxic fumes and other pollutants, while weldable alloys that reduce the need for pre- and post-heat treatment could simplify the welding processes used in the petrochemical and energy industries. Additionally, this R&D can improve productivity and save considerable amounts of energy by reducing or eliminating pre- and post-heat treatment.

The industry must also develop environmentally friendly welding processes that include low-weld fume emissions and spatter generation, and formulate innovative filler materials that do not present health hazards (Energetics, 2000).

# BIBLIOGRAPHY

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## INTRODUCTION

Cogent Regulatory Science. 2002. Web site.

Baker & Hostetler, LLP. 2002. "Executive Alert: EPA Brings the Hammer Down." <<http://www.bakerlaw.com/aboutus/news/pdfs/EPAMay2002.pdf>>

Duckett. 2002. "Environmental Analysis: Environmental Management Challenges." *Industrial Heating* <<http://www.industrialheating.com/>>

## ADVANCED CERAMICS

Korean Institute of Ceramic Engineering and Technology. <[http://amaec.kicet.re.kr/cd\\_astm/PAGES/C1286.htm](http://amaec.kicet.re.kr/cd_astm/PAGES/C1286.htm)>

Abraham, Thomas. "Growth Prediction Lowered for U.S. Advanced Ceramics." *Ceramic Industry Magazine Online* <[http://www.ceramicindustry.com/CDA/ArticleInformation/features/BNP\\_\\_Features\\_\\_Item/0,2710,61633,00.html](http://www.ceramicindustry.com/CDA/ArticleInformation/features/BNP__Features__Item/0,2710,61633,00.html)>

Freedonia Group, Inc., and Mind Branch. "Advanced Ceramics." <[http://www.mindbranch.com/catalog/print\\_product\\_page.jsp?code=R154-639](http://www.mindbranch.com/catalog/print_product_page.jsp?code=R154-639)>

"Advanced Ceramics Experiences Severe Downturn; Recovery Expected in Late 2002 or 2003." *Ceramic Industry Magazine Online* <[http://www.ceramicindustry.com/CDA/ArticleInformation/features/BNP\\_\\_Features\\_\\_Item/0,2710,82241,00.html](http://www.ceramicindustry.com/CDA/ArticleInformation/features/BNP__Features__Item/0,2710,82241,00.html)>

Freedonia Group, Inc., and MarketResearch.Com. December 1, 2000. "World Advanced Ceramics." <<http://www.newsletters.com/map/prod/405686.html>>

National Science Foundation. June 18, 1999. "International Patenting Trends in Advanced Ceramics: Ceramics." <<http://www.nsf.gov/sbe/srs/issuebrf/sib99350.htm>>

U.S. Advanced Ceramics Association. "What are Advanced Ceramics?" <<http://www.advancedceramics.org/#whatareac>>

Abraham, Thomas. *Advanced Ceramics Opportunities* (Business Communications Company, Inc., September 1997).

The Industrial College of Armed Forces, National Defense University. 1993. *Baseline Industry Analysis: Advanced Ceramics Industry*.

University of Western Australia, Department of Mechanical and Materials Engineering. 2002. *Ceramic Processing - Powder Analysis*.

Environmental Protection Agency, Office of Air Quality Planning and Standards Emission Factors and Inventory Group. June 1996. *Ceramic Products Manufacturing AP-42*.

The Industrial College of Armed Forces, National Defense University. 1993. *Baseline Industry Analysis: Advanced Ceramics Industry*.

Helsinki University of Technology. "Pulsed Laser Deposition." <<http://www.hut.fi/Units/AES/projects/plaser/pld.htm>>

The American Ceramic Society. "Ceramic Fact Sheet." <<http://www.acers.org/news/factsheets/eviroment.asp>>

U.S. Advanced Ceramics Association and Oak Ridge National Laboratory for the Office of Industrial Technologies, U.S. Department of Energy. December 1998. *Opportunities for Advanced Ceramics to Meet the Needs of the Industries of the Future*.



U.S. Department of Energy. December 2000. *Advanced Ceramics Technology Roadmap: Charting our Course*.

United States Advanced Ceramics Association and The Aluminum Association; Prepared for the U.S. Department of Energy, Office of Industrial Technologies. February 2001. *Applications for Advanced Ceramics in Aluminum Production*.

Kaniuk, John. Zircoa. *Advanced Ceramics*. Personal email, April 23, 2003.

Kaniuk, John. Zircoa. *Advanced Ceramics*. Personal email, May 2, 2003.

Kaniuk, John. Zircoa. *Advanced Ceramics*. Personal email, May 15, 2003.

### **CARBON PRODUCTS**

Battelle. 1994. *Brief Characterizations of the Top 50 U.S. Commodity Chemicals*.

Carbon Industry Vision. 1998. *The Carbon Products Industry Vision for the Future*.

U.S. Department of Commerce. 2003. *Annual Survey of Manufacturers: Statistics for Industry Groups and Industries 2001*.

U.S. Department of Energy, Office of Industrial Technologies. 1997. *Energy and Environmental Profile of the U.S. Aluminum Industry*.

Emad, Fawzi, et al. 1996. "In-Line Inspection of Carbon Anodes for Use in Aluminum Production." *Light Metals 1996*.

U.S. Environmental Protection Agency. 2003. "NET Facility SIC Report." <<http://www.epa.gov/air/data/reports.html>>

U.S. Environmental Protection Agency. 1996. *Primary Aluminum Industry: Technical Support Document for Proposed MACT Standards*.

U.S. Environmental Protection Agency. 1996a. *Basis and Purpose Document for the Development of Proposed Standards for the Primary Aluminum Industry*.

U.S. Environmental Protection Agency. 1995. *Profile of the Nonferrous Metals Industry* EPA 310-R-95-010.

U.S. Environmental Protection Agency. 1995a. *Compilation of Air Pollutant Emission Factors, Vol. I: Stationary Point and Area Sources* AP-42.

Foosnaes, T., et al. "Waste Tar Firing System for Baking Furnaces." *Light Metals 1994*.

Garbarino, Ron and Tonti, Robert. "Desulfurization and its Effect on Calcined Coke Properties." *Light Metals 1993*.

International Trade Administration. 2003. <[http://www.ita.doc.gov/td/industry/otea/industry\\_sector/tables\\_naics.htm](http://www.ita.doc.gov/td/industry/otea/industry_sector/tables_naics.htm)>

Keller, Felix. "Waste Materials in Anode Manufacturing: An Overview." *Light Metals 1994*.

Richards, Nolan. Personal communication, 1997.

### **FORGING**

AIM Market Research. 2002. *Offshore Forgings Competitive Market Study, May*.

EC21. 2002. Web site.

Engineering Export Promotion Council. 2002. Web site.

Forging Industry Association. 2002. Web site.

Forging Industry Educational and Research Foundation. 1997. *Forging Industry Technology Roadmap*.

Industrial Heating. 2002. Web site.

IMEch E Conference Transactions. "Forging and Related Technology (ICFT' 98)."

Olsen, D.R. 1997. *Pilot Test of Pickling Process to Determine Energy and Environmental Benefits and Economic Feasibility* DOE/EE/15657-T1.

Penton Media Inc. 2002. "Forging: Industry Facts and Figures." July/August.

RSR Group Fasteners and Forgings. 2002. Web site.

U.S. Department of Commerce. 2001. *Annual Survey of Manufactures*.

U.S. Department of Commerce, International Trade Association. 2002. Web site.

U.S. Department of Energy, Office of Industrial Technologies. 2002. *A HotEye™ - Based Coordinate Measuring Machine for the Forging Industry*.

U.S. Department of Commerce. 1999. *Pollution Abatement Cost and Expenditures*.

U.S. Environmental Protection Agency, Office of Compliance. September 1995. *Sector Notebook - Project, Profile of the Fabricated Metal Products Industry*.

## HEAT TREATING

ASM, International. 1999. *R&D Plan for the Heat Treating Community*.

U.S. Environmental Protection Agency. 1992. *Guides to Pollution Prevention: Metal Casting and Heat Treating Industry* EPA/6251R-92/009.

Fan. 1994. *Heat Treating: Proceedings of the International Heat Treating Conference*.

Gas Technology Institute. June 1998. *Composite Radiant Tubes: Opportunity for the Heat Treating Industry*.

Gas Technology Institute. 2002. *High-Performance, Low-NO<sub>x</sub> Industrial Burner*.

Heat Treating Society. 2002. <[http://www.asminternational.org/MStemplate.cfm?Site=Heat\\_Treating\\_Society](http://www.asminternational.org/MStemplate.cfm?Site=Heat_Treating_Society)>

Industrial Heat Equipment Association (IHEA). 1999. "U.S. Imports Exports of Industrial Furnaces and Ovens." Press Release.

Industrial Heat Equipment Association (IHEA). 2003. "Orders Show Decline for First Two Quarters of 2002." Press Release.

International Trade Administration. "NAICS Trends Tables." Web site.

JT Research, LLC. "The Metal Heat Treating Industry 2000." Web site.

Mikropul. 2003. "Mikropul Wet Scrubbers." Web site.

Rich, R. March 1996. "Heat Treating: Proceedings of the 16<sup>th</sup> Conference." Presentation.

Thekdi, Arvind. 2002. Aluminum presentation.

Topmiller, J.E. and R. L. Denison. March 1996. "Heat Treating: Proceedings of the ASM Heat Treating Society Conference." Presentation.

U.S. Department of Commerce, Bureau of Economic Analysis, Industry Economics Division. 2001. Internet, HeatTreatingSales.xls.

U.S. Department of Commerce, U.S. Census Bureau. 2002. *Pollution Abatement Costs and Expenditures: 1999*.

Welling. Personal communication, 2002.

## POWDER METALS

Antony, L. and Reddy, R. 2003. "Processes for Production of High-Purity Metal Powders." *JOM: A Publication of The Minerals, Metals, & Materials Society* 55 (03): 14-18.

Apelian, D., Healy, J., Gummesson, P., and Kasouf, C. "Powder Metallurgy Parts." In *U.S. Industry in 2000: Studies in Economic Performance* (The National Academy Press, 2000) 103-122.

Apelian, D., Healy, J., Gummesson, P., and Kasouf, C. "Competitive and Economic Performance in the Powder Metallurgy Parts Industry." In *America's Industrial Resurgence: Sources and Reports* (National Academy of Sciences, 1997).

ASM International Handbook Committee. *Powder Metal Technologies and Applications*, Vol. 7 of *ASM Handbook* (ASM International, 1998).

Bocchini, G., Bressan, A., and Scipione, A. 2001. "Technical Requirements of an 'Ideal' Sinter-Hardening Furnace." *P/M Science & Technology Briefs* 3 (4): 12-17.

Bocchini, G. 1983. "Energy Requirements of Structural Components: Powder Metallurgy v. Other Production Processes." *Powder Metallurgy* 26 (2): 101-113.

Cooper, C. "Powder Metallurgy Innovations." *Gear Technology* <[www.geartechnology.com/mag/archive/Pm.htm](http://www.geartechnology.com/mag/archive/Pm.htm)>

Diaz-Triana, A. and Isaacs, J. 2002. "Environmental Trends for the U.S. Powder Metallurgy Industry." *Proceedings of the 2002 World Congress on Powder Metallurgy & Particulate Materials* 12.35-49.

Diesch, F. and Schulz, G. "Gas Atomization of Prealloyed MIM Powders in Bulk Quantities." In *Advances in Powder Metallurgy & Particulate Materials*, eds. C. Rose and M. Thibodeau (Princeton: Metal Powder Industries Federation, American Powder Metallurgy Institute, 1999), 1.49-121.

Elsevier Science, Ltd. 2001. "PIM sales forecast to treble by 2010." *Metal Powder Report* 56 (2): 22-25.

Elsevier Science, Ltd. 2002. "The advantages of all-around pressure." *Metal Powder Report* 57 (2): 18-21.

EPRI Center for Materials Production. *Industry Segment Profile - SIC 33991: Metal Powder Production (000000000001000133)* (Columbus: EPRI, 2000).

European Powder Metallurgy Association. 2003. <<http://www.epma.com>>

German, R. and Cornwall, R. 2001. "Powder Injection Molding: Year 2000 Market and Industry Report." *International Journal of Powder Metallurgy* 37 (1): 40-44.

German, R. 2000. "Powder Injection Molding: Current and Long Term Outlook." *International Journal of Powder Metallurgy* 36 (3): 31-36.

German, R. and Cornwall, R. 1997. "Worldwide Market and Technology for Powder Injection Molding." *International Journal of Powder Metallurgy* 33 (4): 23-27.

Isaacs, J. and Diaz-Triana, A. 2002. "U.S. P/M Industry: Is Economic Competitiveness Affected by Environmental Costs?" *Proceedings of the 2002 World Congress on Powder Metallurgy & Particulate Materials* 12.25-34.

Hauck, P. 2000. "Powder Injection Molding: Current and Long Term Outlook." *International Journal of Powder Metallurgy* 36 (3): 29-30.

Ito, S. 1996. "Global General Session: Japan, Asia, and Oceania." In *Advances in Powder Metallurgy & Particulate Materials*, eds. T. Cadle and K. Narasimhan (Princeton: Metal Powder Industries Federation, American Powder Metallurgy Institute, 1996), A.17-24.

Johnson, P. 2002. "P/M Technology Trends - 2002." *International Journal of Powder Metallurgy* 38 (3): 43-51.

- Johnson, P. 1999. "P/M Technology Trends - 1999." *International Journal of Powder Metallurgy* 35 (3): 13-19.
- Johnson, P. 1997. "P/M Technology Trends - 1997." *International Journal of Powder Metallurgy* 33 (3): 13-19.
- Johnson, P. 1996. "P/M Industry Trends: New Technologies Propel P/M Growth." *International Journal of Powder Metallurgy* 32 (2): 145-153.
- Johnson, P. 1990. "PM '90: International Trends and Developments." *International Journal of Powder Metallurgy* 26 (4): 382-387.
- Kasouf, C., Apelian, D., and Gummeson, U. 2002. "Opportunities and Challenges for P/M: Retrospective and Prospective Views of the Industry." *International Journal of Powder Metallurgy* 38 (4): 72-74.
- Isaacs, J. and Diaz-Triana, A. 2002. "U.S. P/M Industry: Is Economic Competitiveness Affected by Environmental Costs?" *Proceedings of the 2002 World Congress on Powder Metallurgy & Particulate Materials* 12.25-34.
- ASM International Handbook Committee. *Powder Metal Technologies and Applications*, Vol. 7 of *ASM Handbook* (ASM International, 1998).
- Lindskog, P. F. "P/M Structural Parts in Europe Today." In Vol. 1 of *Advances in Powder Metallurgy & Particulate Materials*, eds. C. Lall and A. Neupaver (Princeton: Metal Powder Industries Federation, American Powder Metallurgy Institute, 1994), 11-19.
- Metal Powder Industries Federation. "Conventional Powdered Metal Components." <<http://www.mpif.org/design/conventional.pdf>>
- Metal Powder Industries Federation. "What is Powder Metallurgy?" <<http://www.mpif.org/technology/whatis.html>>
- Metal Powder Industries Federation; U.S. Department of Energy, Office of Industrial Technologies. *PM<sup>2</sup> Industry: Vision and Technology Roadmap* (Princeton, 2001).
- Metal Powder Industries Federation. *White Paper Report on the Powder Metallurgy Industry* (Princeton: Metal Powder Industries Federation, 1999).
- U.S. Census Bureau. "Powder Metallurgy Parts Manufacturing." In *1997 Economic Census: Manufacturing, Industry Series*. (U.S. Department of Commerce, 1997).
- U.S. Environmental Protection Agency (2002). 40 CFR – Protection of the Environment; Chapter I: Environmental Protection Agency; Subchapter N – Effluent Guidelines and Standards; Part 471 – Nonferrous Metals Forming and Metal Powders Point Source Category; Subpart J – Metal Powders Subcategory.
- U.S. Environmental Protection Agency. "Chapter 8: Toxics Release Inventory Data for Primary Metals." In *Toxics Release Inventory (SIC 33)* (1998), 285-327.
- White, D.G. 2002. "State-of-the-P/M Industry - 2002." *Proceedings of the 2002 World Congress on Powder Metallurgy & Particulate Materials* 1.1-6.
- White, D.G. 2001. "State-of-the-P/M Industry - 2001." *Proceedings of the 2001 World Congress on Powder Metallurgy & Particulate Materials* 1-15.
- White, D.G. "State-of-the-P/M Industry - 1999." In *Advances in Powder Metallurgy & Particulate Materials*, eds. C. Rose and M. Thibodeau (Princeton: Metal Powder Industries Federation, American Powder Metallurgy Institute, 1999), XIX – XXXI.
- White, D.G. "The Challenges of Growth." In *Advances in Powder Metallurgy & Particulate Materials*, eds. J. Oakes and J. Reinshagen (Princeton: Metal Powder Industries Federation, American Powder Metallurgy Institute, 1998), XVII – XXIX.
- White, D. G. "State of the North American P/M Industry: Challenges for the 21<sup>st</sup> Century." In *Advances in Powder Metallurgy & Particulate Materials*, eds. R. McKotch and R. Webb (Princeton: Metal Powder Industries Federation, American Powder Metallurgy Institute, 1997), 1-3 - 1-16.

White, D. G. "P/M in North America." In *Advances in Powder Metallurgy & Particulate Materials*, eds. T. Cadle and K. Narasimhan (Princeton: Metal Powder Industries Federation, American Powder Metallurgy Institute, 1996), A-3 - A-16.

White, D. G. "State of the North American P/M Industry: P/M's Promise Realized." In *Advances in Powder Metallurgy & Particulate Materials*, eds. M. Phillips and J. Porter (Princeton: Metal Powder Industries Federation, American Powder Metallurgy Institute, 1995), 1-3 - 1-9.

White, D. G. "State of the North American P/M Industry: 50 Years of Progress." In Vol. 1 of *Advances in Powder Metallurgy & Particulate Materials*, eds. C. Lall and A. Neupaver (Princeton: Metal Powder Industries Federation, American Powder Metallurgy Institute, 1994), 1-10.

White, D. G. "State of the North American P/M Industry: P/M on the Rebound." In Vol. 1 of *Advances in Powder Metallurgy & Particulate Materials*, eds. A. Lawley and A. Swanson (Princeton: Metal Powder Industries Federation, American Powder Metallurgy Institute, 1993), 1-12.

White, D. G. "State of the P/M Industry Report: Exploring New Horizons." In Vol. 1 of *Advances in Powder Metallurgy & Particulate Materials*, eds. J. Capus and R. German (Princeton: Metal Powder Industries Federation, American Powder Metallurgy Institute, 1992), 1-7.

White, D. G. "Global General Session I: What's Ahead for P/M?" In Vol. 1 of *Advances in Powder Metallurgy*, eds. L. Pease III and R. Sansoucy (Princeton: Metal Powder Industries Federation, American Powder Metallurgy Institute, 1991), 1-14.

Williams, B. 2001. "Setting Standards and Getting it Right!" *Metal Powder Report* 56 (12): 14-18.

## WELDING

ASM International, *Metals Handbook Desk Edition, 2<sup>nd</sup> Edition*. (Materials Park, OH, 1998).

American Welding Society. 2003. *Guide for Estimating Welding Emissions for EPA and Ventilation Permit Reporting* (and Annex Z: Typical emission Factors for Total Fume and Elemental Fume content for Common Welding Processes and Electrodes) AWS F1.6:2003. Fax transmission, June 2003.

American Welding Society. *Welding-Related Expenditures, Investments, and Productivity Measurement in U.S. Manufacturing, Construction, and Mining Industries* (Miami, FL: American Welding Society, 2002).

American Welding Society. *Vision for the Welding Industry* (Miami, FL: American Welding Society, 1999).

U.S. Department of Labor, Bureau of Labor Statistics. *Occupational Outlook Handbook, 1996-97 Ed.* (Washington, D.C.: U.S. Department of Labor, 1996).

U.S. Department of Commerce, Bureau of the Census. *Annual Survey of Manufacturers 2000*. M(00)AS-1 (Washington, D.C.: U.S. Department of Commerce, 2002).

Energetics, Incorporated. *Welding Technology Roadmap* (Washington, D.C.: U.S. Department of Energy, Office of Industrial Technologies, 2002).

U.S. Environmental Protection Agency. *Development of Particulate and Hazardous Emission Factors for Electric Arc Welding (AP 42 - Section 12.19) - Revised Final Report*. MRI-MR4601-02.WLD. (Research Triangle Park, NC: U.S. EPA, 1994).

U.S. Department of Commerce, International Trade Association. 2003 (last rev). "Welding and Soldering Equipment Manufacturing."  
<[http://www.ita.doc.gov/td/industry/otea/industry\\_sector/tables/3548.txt](http://www.ita.doc.gov/td/industry/otea/industry_sector/tables/3548.txt);  
[http://www.ita.doc.gov/td/industry/otea/industry\\_sector/tables\\_naics/333992.htm](http://www.ita.doc.gov/td/industry/otea/industry_sector/tables_naics/333992.htm).>

Pekkari, Bertil. November 2002. "Speed Up Your Environmental Programmes." Presented at *I/W Asian Pacific International Congress*, Singapore.

Pekkari, Bertil. 2000a. November 8, 2000. "Trends in Joining and Cutting in a Sustainable World." Presented at *The Richard Weck Lecture* at the Institute of Materials, London, UK.

Pekkari, Bertil. 2000b. "Welding and Cutting in a Sustainable World." *Canadian Machinery and Metalworking* 95 (2).

Pekkari, Bertil. 1999. "Welding and Cutting in a Sustainable World." *Canadian Machinery and Metalworking* 94 (8).

Remich, Norman. 2002. "Welding Widespread." *Appliance Manufacturer* 50 (6).

Schuh, Jerry and Indy, Datta. 1998. "Welding Can Pay for Itself: How to Calculate Energy Efficiency and Savings for a Welding Power Source." *American Machinist* 142 (4).

Weber, Rick. 2003. "How to Save 20 percent on Welding Costs." *Trailer/Body Builders* January 1, 2003.

Weman, Klas. 1999. "Energy Efficiency in Welding." *Svetsaren* 1 (2).







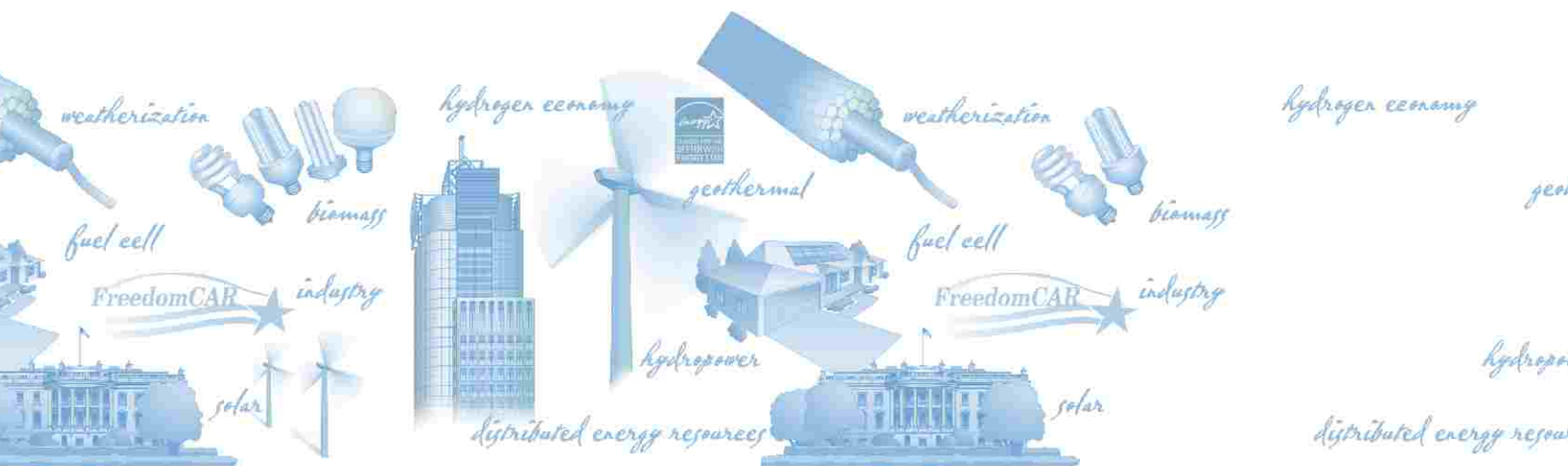
## A Strong Energy Portfolio

### for a Strong America

*Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. By investing in technology breakthroughs today, our nation can look forward to a more resilient economy and secure future.*

*Far-reaching technology changes will be essential to America's energy future. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a portfolio of energy technologies that will:*

- *Conserve energy in the residential, commercial, industrial, government, and transportation sectors*
- *Increase and diversify energy supply, with a focus on renewable domestic sources*
- *Upgrade our national energy infrastructure*
- *Facilitate the emergence of hydrogen technologies as vital new "energy carriers".*



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